Topic report 3/2001

Air quality in larger cities in the European Union

A contribution to the Auto-Oil II programme

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Summary

This report summarises work on the 'generalised empirical approach' (GEA) developed for air-quality evaluation in the second Auto-Oil programme (AOP-II).

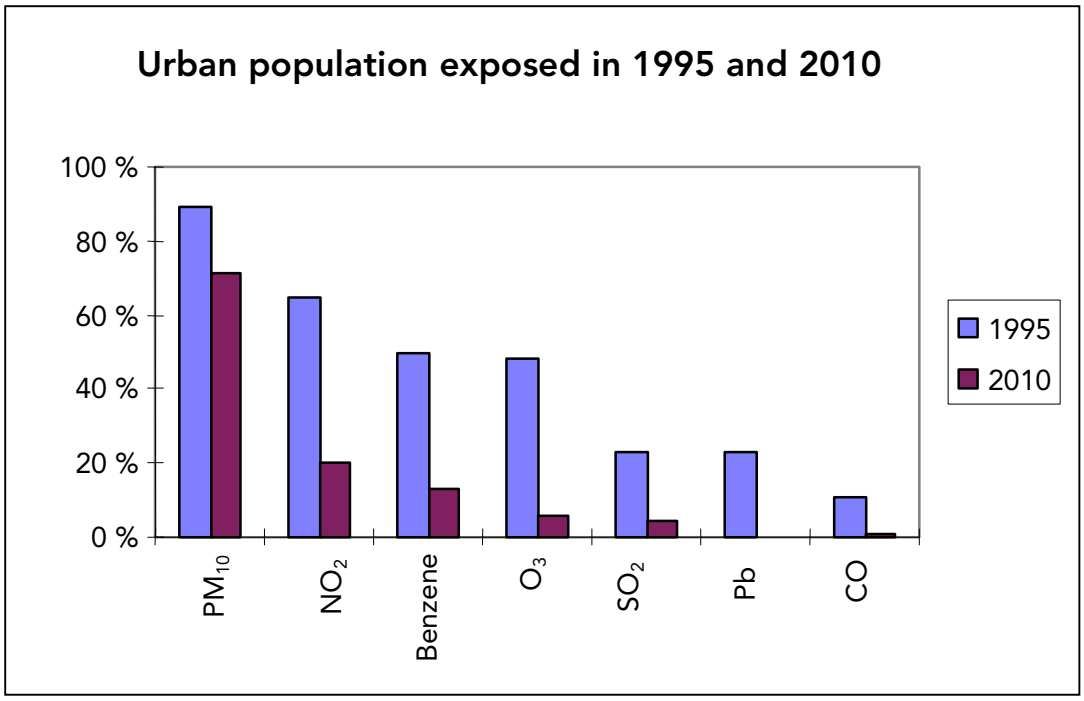
The goal of the GEA is to estimate the size of the urban population living in cities within the European Union, which are not in compliance with air-quality objectives in future years and to estimate additional emission reductions needed to reach compliance.

In the GEA study, simple tools are used to calculate, in a consistent way, air quality in a relatively large number of cities. This allows for a generalisation of the results on the scale of the whole European Union. The calculated future air quality provides information on the possible future frequency and severity of exceedance of air-quality objectives and on the fraction of EU urban population potentially exposed.

In this study, the air quality in about 200 urban agglomerations within the EU is calculated for a reference year (1995 or 1990) and for the year 2010, assuming the 'Auto-Oil II' programme base case scenarios. The parameter calculated is the urban background air pollution concentration, which is representative of the concentration in most of the urban area, with the exception of places under direct influence of emission sources, such as street traffic.

The air pollutants considered in the GEA study are sulphur dioxide (SO_2), nitrogen dioxide (NO_2), fine particulates (PM_{10}), lead (Pb), ozone (O_3), carbon monoxide (CO), and benzene; some results are also reported for benzo(a)pyrene (B(a)P). In this report, all these pollutants, except O_3, have been treated as 'inert' and chemical degradation at the urban scale was neglected. NO_2 is a special case; its concentration is derived from the concentration of NO_x (handled as an inert species) using an empirical relationship.

The calculated urban background concentrations in the set of 200 modelled cities were combined with urban population data to estimate the fraction of the urban population exposed to concentrations above agreed or proposed air-quality standards. For 2010, this fraction is calculated to decrease strongly compared to the reference year. The calculations indicate, however, that the air-quality standards will still be exceeded in the future; the most serious problems are exceedances of the short- and long-term objectives for PM_{10} and exceedance of the long-term objective for NO_2. The calculated reductions in exposure of the population following improvements in urban air quality are shown in the figure below.


Urban population exposed in 1995 and 2010
100 %
80 %
60 %
40 %
20 %
0 %
PM10
NO2
Benzene
O3
SO2
Pb
CO
1995
2010

Contents

1. Organisation and scope

This report summarises work on the 'generalised empirical approach (GEA)' developed for air-quality evaluation in the second Auto-Oil programme (AOP-II).

This work was performed under the responsibility of the European Environment Agency. The European Topic Centre on Air Quality (ETC/AQ), in collaboration with the European Topic Centre on Air Emissions (ETC/AE), carried out the work as part of the EEA work programme. The institutes contributing to the AOP-II-GEA project were RIVM, University of Thessaloniki, NILU, DNMI (all ETC/AQ), and TNO (ETC/AE).

The work started in January 1998, based on the work plan as presented in Annex C to the paper 'Methodology proposed for air-quality modelling during Auto-Oil II' which was agreed in the meeting of AOP II Working Group 1 in January 1998. Progress in the work was reported, presented and discussed in various meetings of the Technical Subgroup on Urban Air-Quality Modelling, and in Working Group 1 (see CEC, 2000) for an overview of the organisational structure of Working Group 1).

The goal of the GEA is to estimate the fraction of the urban population that is living in European cities which may not be in compliance with agreed or proposed air-quality objectives in future years and to estimate additional emission reductions needed to reach compliance.

With the GEA, simple robust tools are used to calculate, in a consistent way, air quality in a relatively large number of European cities. The consistency allows for a generalisation of the results on the scale of the whole European Union. The projected air quality provides information on the frequency and severity of exceedance of air-quality objectives and on the fraction of EU urban population potentially exposed.

In this study, the air quality in about 200 urban agglomerations within the EU is calculated for a reference year (1995 or 1990) and for the year 2010, assuming the AOP II base case scenarios (SENCO, 1999). The key parameter calculated is the urban background air pollution concentration, which is representative of the concentration in most of the urban area, but not for places under direct influence of close emission sources, such as street traffic. Averaging times for the calculated concentrations are in accordance with the air-quality objectives as presented in Table 1.1.

The pollutants considered in the GEA study are sulphur dioxide (SO_2), nitrogen dioxide (NO_2), fine particulates (PM_{10}), lead (Pb), ozone (O_3), carbon monoxide (CO), and benzene; some results are also reported for benzo(a)pyrene (B(a)P). In this report, all these pollutants, except O_3, have been treated as 'inert'. Strictly speaking, this is not correct; since all these pollutants, except Pb, are subject to (photo)chemical conversion. However, compared to the residence time over an urban area, the chemical lifetime of these pollutants is large. NO_2 is a special case; its concentration is derived from the concentration of NO_x (handled as inert) using an empirical relationship.

The study is complementary to the more detailed urban impact assessment (see CEC, 2000), since it covers, for the same pollutants, environmental objectives, scenarios and years, and a larger number of cities, assessed with simple models, on

the basis of simplified urban emission estimates. While the simplifications may obviously introduce additional uncertainties, the advantage of the approach lies in its consistency and sample size. In the urban impact assessment study, as applied to the 10 selected cities, the methodology for emission inventory and air-quality model calculation, though state-of-the-art and quite detailed, differs from city to city.

In this report, the results of the GEA study are presented and the methodology is documented. Methods and input data are briefly presented in Chapter 2; for more information, see Annex 1. In Chapter 3, results for the reference case (in most cases 1995, for some pollutants 1990) are discussed and the projected base case results for 2010 are presented in Chapter 4. A discussion on the results and a comparison with the detailed urban impact assessment approach are given in Chapters 5 and 6; conclusions are presented in Chapter 7.

Table 1.1. Environmental objectives used in this study

Pollutant	Averaging period	AQ standard/objective
SO_2 ([1])	1 hour	350 µg/m^3 not to be exceeded more than 24 times in a calendar year
SO_2 (1)	24 hours	125 µg/m^3 not to be exceeded more than three times in a calendar year
NO_2 ([1])	1 hour	200 µg/m^3 not to be exceeded more than 18 times in a calendar year
NO_2 ([1])	Calendar year	40 µg/m^3
PM_{10} ([1])	24 hours	50 µg/m^3 not to be exceeded more than seven times in a calendar year
PM_{10} ([1])	calendar year	20 µg/m^3
CO_2 ([2])	8 hours	10 mg/m^3
O_3 ([3])	daily 8-h max	120 µg/m^3 not to be exceeded more than 20 days per calendar year
Benzene ([2])	calendar year	5 µg/m^3
Pb ([1])	calendar year	0.5 µg/m^3
B(a)P ([4])	calendar year	1 ng/m^3

([1]) Limit values for the protection of human health from the directive on SO_2, NO_2, PM_{10} and Pb (1999/30/EC).
([2]) Limit values for the protection of human health from proposed directive on CO and benzene (document COM(98) 591 final, 1/12/98).
([3]) Target value for the protection of human health from proposed daughter directive on ozone (COM(99)125).
([4]) Currently no standard for B(a)P has been proposed by the Commission. The Netherlands has set a limit value of 1 ng/m^3 as annual mean. WHO estimates the excess risk of dying from cancer following lifetime exposure to PAH as 8.7 x 10^{-5} (ng/m^3)$^{-1}$. Assuming an annual mean concentration for B(a)P of 1 ng/m^3 and assuming that PAH exposure is dominated by B(a)P, this leads to a lifetime risk of about 10^{-4}. In this study an objective of 1 ng/m^3 is used.

2. Methods and input data

2.1. Selection of cities and data collection

2.1.1. Selection of cities

The selection of cities is described in Annex 1. Selection criteria were size (all conurbations with more than 250 000 inhabitants) and availability of air-quality monitoring data. This selection of 120 was extended with about 50 smaller cities with reliable monitoring data.

The selected cities are presented in Map 1 and listed in Annex 2. In Table A1 and Figure A1 in Annex 1, some statistical information on selected cities is presented. The selected cities cover almost 40 % of the EU urban population.

The calculations of ozone concentrations were carried out for a sub-set of 57 cities, including almost all cities with more than 0.5 million inhabitants. On a country basis, these 57 cities represent 55–100 % of the population in cities selected for inert pollutant modelling.

The 10 cities analysed in the urban impact assessment are included in the selection.

2.1.2. Estimation of urban area

For each city the size of the urban area was estimated by the ETC on Land Cover (ETC/LC, Robert Enesund, private communication, 1998) by a procedure described in ETC/LC (1997). Basic input is the Corine land cover data set and the 'major land cover types of Europe' (MLCT) data set. More information can be found in Annex 1.

2.1.3. Collection of AQ monitoring data

Measurement data have been collected from as many of the selected cities as possible for SO_2, NO_2, and particulate matter (PM_{10}) and Pb, covering the years 1992–96.

The sources of the data are mainly the Airbase database (EEA, 1999), the database for air quality in Europe 1993 report (Larssen and Hagen, 1996), data collected by the EC Working Group on Particulate Matter and National Data. For further information, see Annex 1.

2.2. Urban emissions

Urban emissions were estimated using a top-down approach, proposed by the Topic Centre on Air Emissions (EEA, 1996b). While this simple procedure is clearly approximate, it offers the advantage of providing consistent emission estimates for all selected cities in Europe. Estimates were made on the basis of available data:

- national emissions per sector as given in the AOP II base case Version 5 scenario (SENCO, 1999);

- detailed information on emissions from Corinair 90 at a NUTS 3 geographical level and a SNAP1 level of sector detail, available for SO_2, NO_x, CO and VOC (EEA, 1996a).

Emissions for years other than 1990 were not available for any of the pollutants at a NUTS 3 level of detail. Urban emissions for other years were estimated by scaling the 1990 emission data according to the ratio of national emissions (at a SNAP1 level) in 1990 and in the year considered.

Information on 1995 was obtained from SENCO (1999) for NO_x, SO_2, CO, VOC, benzene and PM_{10}; and for B(a)P and Pb from Visschedijk et al. (1999). Additional information on 1994 emissions was obtained from the EEA (1997).

In Annex 1, the methodology is described and results are discussed and compared to available data.

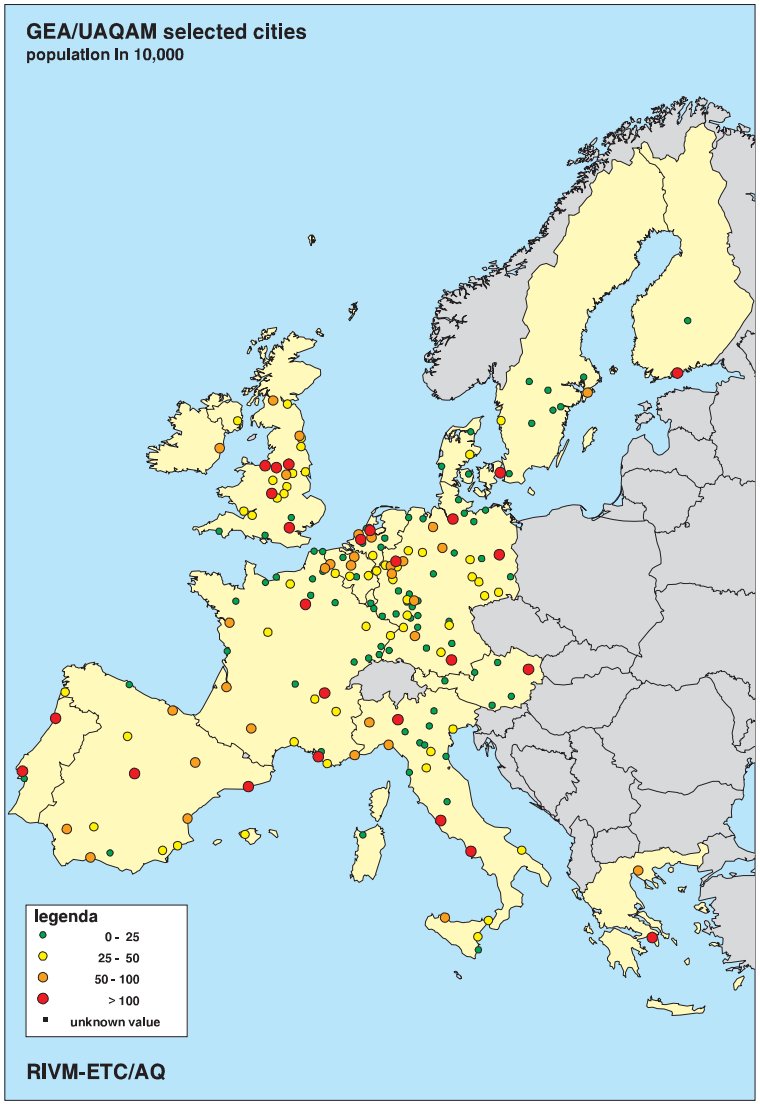
The urban emissions as calculated by these procedures are presented in Annex 3.

2.3. Air pollution models and background concentrations

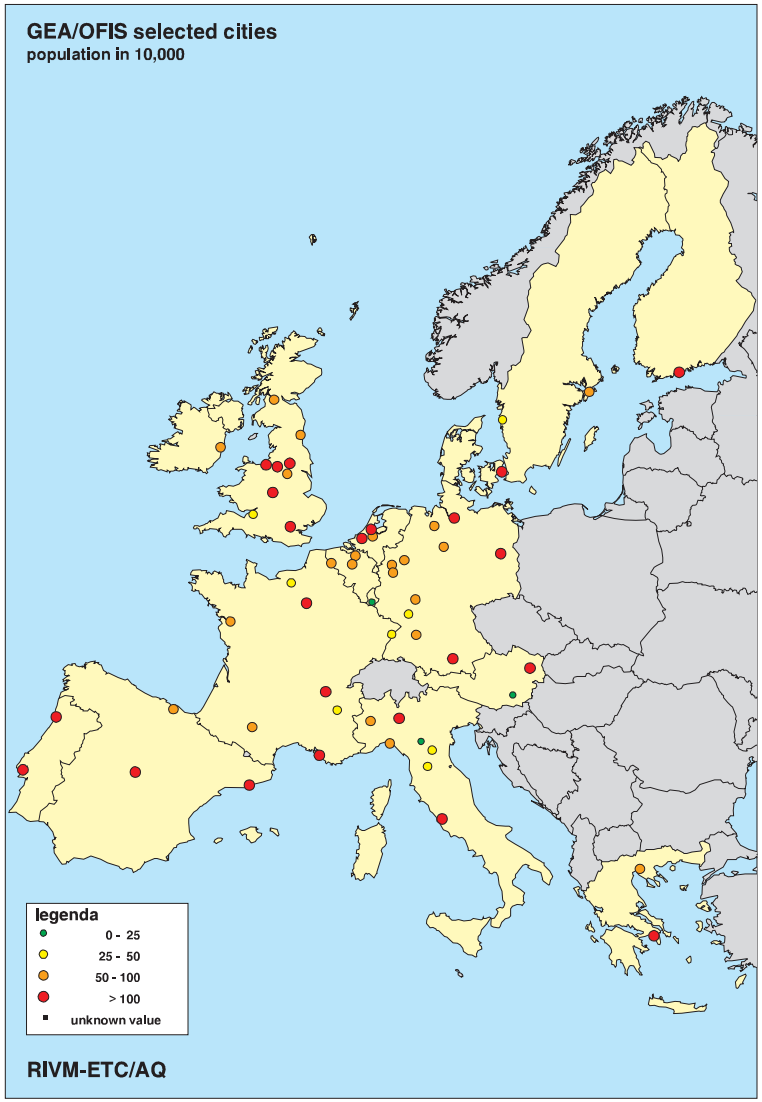
In the GEA study, three air pollution models were used for the calculation of air-quality parameters from urban emissions:

- The cQ model for 'inert' species where sufficient monitoring data were available.
- The UAQAM (urban air-quality assessment model) for 'inert' species in all cities.
- The OFIS (ozone fine structure) model, which was applied to calculate ozone concentrations for a limited number of cities.

These models are presented and briefly discussed in Annex 1.
Information on background concentrations needed for input to these models is also provided in Annex 1.



Map 1. Selected cities for cQ and UAQAM applications

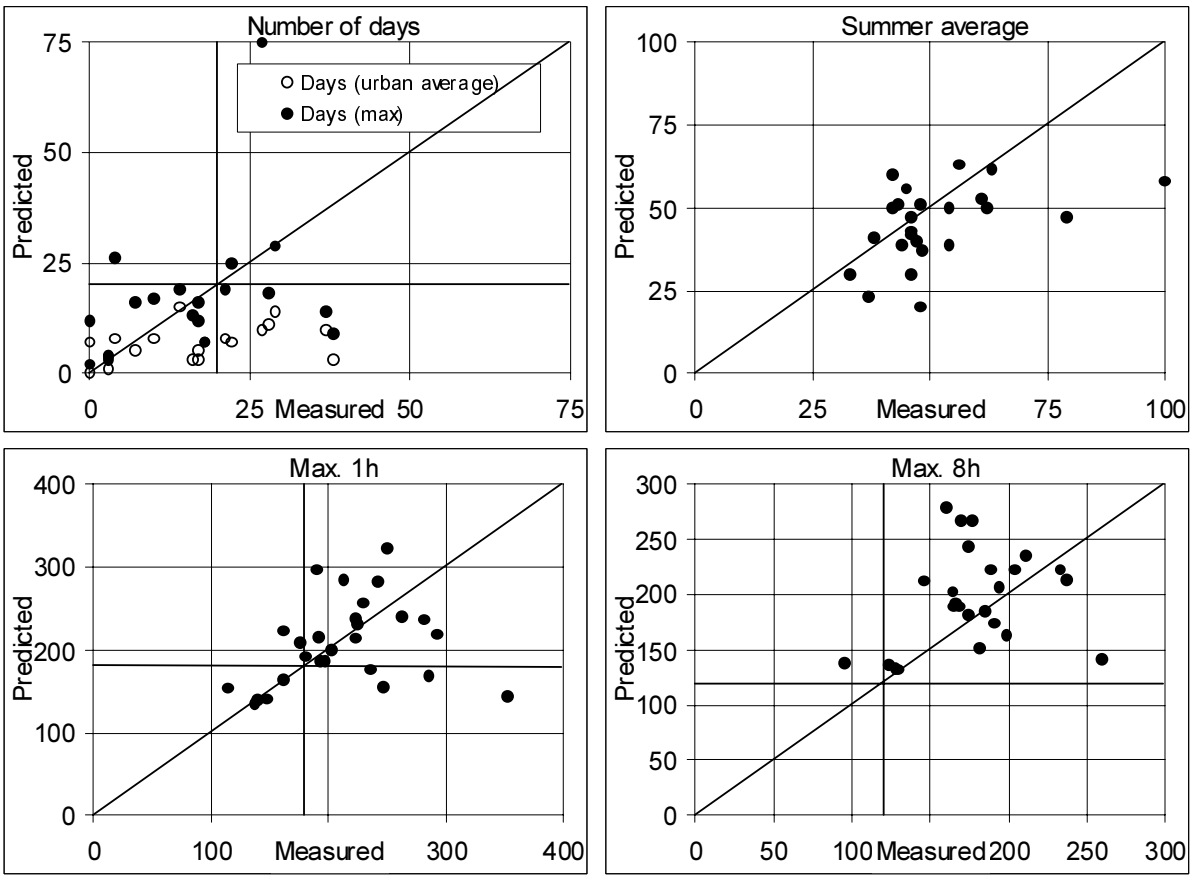


Map 2. Selected cities for OFIS model application

3. Results for the reference case

The reference year is 1995; for lead and B(a)P, no emission data for 1995 are available and 1990 was taken instead. The reference case was modelled using the OFIS model (ozone) and UAQAM (other components). The cQ model was not applied; the measurement data in the reference period were used for parameterisation of the model.

Figure 3.1. OFIS model results for the number of days with the running 8 h mean exceeding 120 μg/m³(upper left; filled circles: maximum number of days; blank circles: urban average), the summer average (upper right), the 1 h maximum (lower left) and the 8 h maximum (lower right) ozone concentrations compared to observations (reference year 1995); the bold lines in the figures refer to air-quality objective (Table 1.1) and to the threshold value for information of the population (180 μg/m³, 1 h average)



3.1. Ozone: 1995

Simulations with the OFIS model were performed for each day between 1 April and 30 September 1995 for 57 cities. Both area and elevated emissions are from the SENCO base case (Version 4) on NUTS 3 level of detail for SO_2, CO, NO_x and NMVOC. It was assumed that each city is surrounded by a suburban ring covering the same area as the urban core and thus the total city emissions were subdivided into urban emissions and suburban emissions with the ratio 2:1. Rural emissions were derived from data supplied by the DNMI at a spatial resolution of 50 km by subtracting the city emissions from the overall emissions within the 150×150 km^2 area surrounding each city.

Figure 3.1 shows scatter plots of calculated against observed number of exceedance days for the running 8 h mean exceeding 120 µg/m^3, the 1 h maximum, 8 h maximum and 6six-month averaged ozone concentrations for all urban areas where measurements for 1995 are available. The measured data were taken from the EEA (1998a) and from the Airbase air-quality database (EEA, 1999).

In general, the agreement between model results and observations is satisfactory. However, reported data for Lyon (146 exceedance days out of approx. 180 summer days) appear unrealistic and inconsistent with data reported under the ozone directive. In addition, sites reporting exceedance days for Copenhagen, Essen and Liverpool are not adequately documented. The model results, however, suggest that the sites in those cities do not represent the areas with the highest ozone levels and that sites in Hamburg, Utrecht and Wien represent the regional rather than the urban background.

In spite of sea-breeze effects implemented in the OFIS model for some coastal urban areas, it appears probable that for cities affected by sea breezes, the complexity of the flow field is not fully reflected in the calculated results. However, the disagreement could well be associated with inaccuracies in the emissions (e.g. the urban and suburban VOC emissions for Athens exceed those reported by EMEP for the Greater Athens area, thus leading to zero VOC emission estimates for the rural area around Athens).

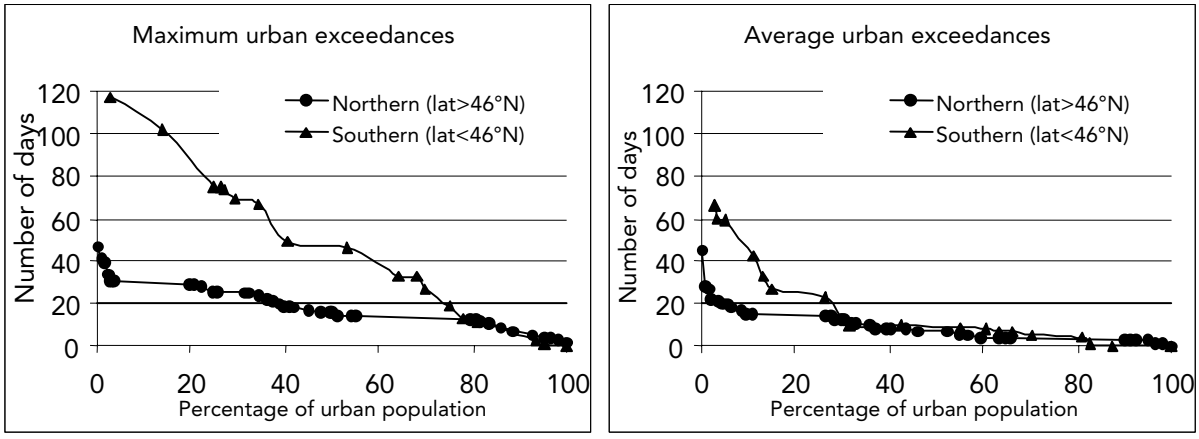
Table 3.1. Statistical analysis for OFIS model results (reference year, 1995)

	Average observed	Average calculated	BIAS	FB	RMSE	NMSE	FAC2
Maximum number of days of exceedance ([1])	18	15	3	0.13	7	0.16	94 %
Summer average (µg/m^3)	48	46	1	0.05	9	0.05	100 %
Maximum 1 h (µg/m^3)	203	214	– 10	– 0.05	45	0.04	100 %
Maximum 8h (µg/m^3)	174	206	– 32	– 0.16	49	0.06	100 %

([1]) No exceedances are observed in Helsinki and Thessaloniki. Those two cities are neglected in the statistical analysis.

A statistical evaluation of the model performance was performed for the above parameters in terms of systematic difference or bias (BIAS), fractional bias (FB), root mean square error (RMSE), normalised mean square error (NMSE) and the fraction of results within a factor of two (FAC2). In this evaluation, a total of three cities (Helsinki, Thessaloniki and Lyon) were excluded since the above-mentioned analysis proved that a comparison between OFIS model results and observations is meaningless. The results of this statistical analysis are presented in Table 3.1 together with the average values derived from the observed and calculated data.

Figure 3.2. Cumulative distribution of days with exceedance of the running 8 h average of 120 μg/m³ ozone (1995) over the population in the modelled cities in northern Europe (circles) and cities in southern Europe (triangles) (left: highest concentration in the urban area; right: concentration averaged over the urban area); according to the proposed ozone directive, exceedance is allowed on not more than 20 days



The statistical evaluation shows a very satisfactory agreement between model predictions and the available measurements.

Ozone exceedance statistics

Figure 3.2 shows the cumulative distribution of the urban area maximum (left) and urban area average (right) number of days with exceedance of the running 8 h average of 120 μg/m³ ozone (reference year 1995) versus the percentage of population subject to these exceedances. The distribution is shown separately for cities in northern Europe (cities north of 46 °N, marked with circles) and cities in southern Europe (cities south of 46 °N, marked with triangles).

Highest maximum values (exceeding 100 days) are calculated for cities in southern Europe. About 75 % of the urban population in southern Europe and about 40 % of the urban population in northern Europe lives in cities where the maximum urban ozone levels exceed the running 8 h average of 120 μg/m³ ozone for more than 20 days. In the EU-15, 48 % of the urban population lives in non-attainment cities. Referring to ozone concentrations averaged over the urban areas, more than 25 % of the urban population in southern Europe and about 5 % of the urban population in northern Europe is exposed to exceedances of the running 8 h average of 120 μg/m³ ozone on more than 20 days.

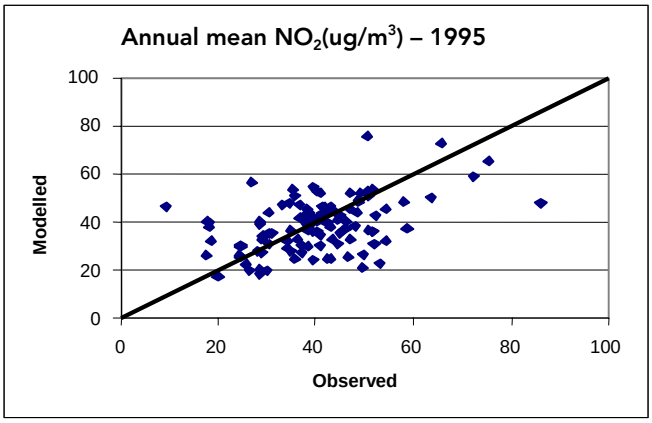
3.2 Nitrogen dioxide: 1995

The UAQAM calculates the urban NO_x concentration as a sum of the background concentration and the contribution from urban emissions. From the calculated NO_x concentration, the NO_2 concentration is estimated using the empirical BUWAL-equation.

Figure 3.3 presents a comparison between observed (period 1992–96) and calculated annual average concentrations. The agreement (with a root mean square error (RMSE) of 12 μg/m³ and 94 % of the deviation within a factor of 2) is reasonable, taking into account limitations in representativeness of the monitoring stations for urban background conditions.

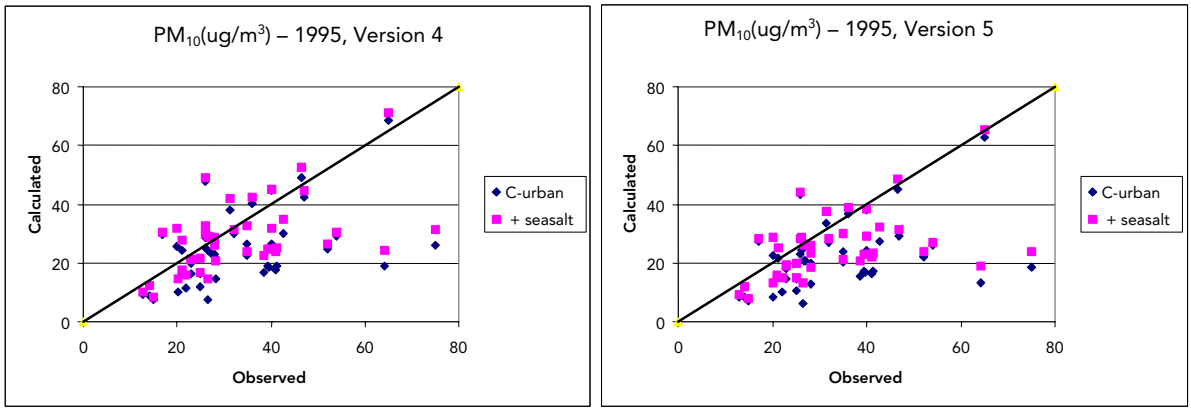
Observations indicate that about 70 % of the urban population is exposed to an annual mean concentration in excess of the objective of 40 µg/m^3; the model estimates this fraction at 65 %.

Figure 3.3. Observed versus modelled urban NO_2 background concentrations; 1995; the observed concentrations cover the period 1992–96



Observations indicate that about 77 % of the urban population lives in cities where the short-term objective is exceeded. The model estimates this fraction at 5 %. This discrepancy can partly be explained by the difference in population size. NO_2 monitoring data are only available for 60 % of the population included in the model calculations.

Figure 3.4. Observed versus modelled PM_{10} concentrations, 1995



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3.3. Fine particulates (PM_{10}): 1995

To illustrate uncertainties in PM_{10} modelling, model calculations were made both for base case Version 4 as well as base case Version 5 emissions. Version 5 has the lowest emissions; the main differences between the two versions are in the assumed emission factors for tail-pipe and non-exhaust transport emissions and in the estimates for waste incinerators.

Figure 3.4 presents a comparison between observed and calculated concentrations using both sets of emission estimates. Observations cover the period 1992–96. In addition to the modelled urban background concentrations, the contribution of sea salt (Eerens et al., 1998) is included. The scatter in the two plots is too large to draw conclusions on the reliability of the calculated data or the two emission sets. For two cities, the modelled concentration strongly deviates from the observed: Lisboa (observed 75 $\mu g/m^3$, calculated 23 $\mu g/m^3$) and Setubal (observed 64 $\mu g/m^3$, calculated 19 $\mu g/m^3$). Here, as well as for many other cities, the (semi)-natural contribution of resuspended soil might be of importance.

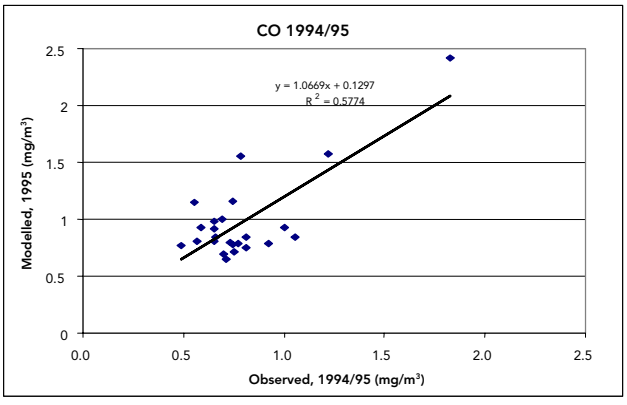
3.4. Carbon monoxide: 1995

For CO, emission estimates for 1995 were made by application of Equation (3) where emission data on country/SNAP 1 level are obtained from the AOP II base case, Version 5 (SENCO, 1999).

A comparison between observed and modelled concentrations is given in Figure 3.5. The observed data are averaged for 1994 and 1995 and obtained for all stations labelled as 'urban background' in Airbase. The modelled data refer to a calculation using 1994 data for both emissions and meteorology. In view of the uncertainties in the estimates of the regional background and the uncertainties in the representativeness of the urban stations, there is a reasonable agreement.

Exceedances of the environmental objective (8 h running average of 10 mg/m^3) were calculated for 11 cities (14 % of the total population of all modelled cities). All of these cities are located in the southern part of Europe.

Figure 3.5. Observed versus modelled urban CO background concentrations



3.5. Sulphur dioxide: 1995

For SO_2, the urban emissions for 1995 were prepared on the basis of SENCO base case Version 5.

Figure 3.6. Observed versus modelled urban SO_2 background concentrations (left); cumulative distribution of exceedance days of the 24 h average of 125 μg/m³ over the population in the modelled cities; reference year 1995(right)

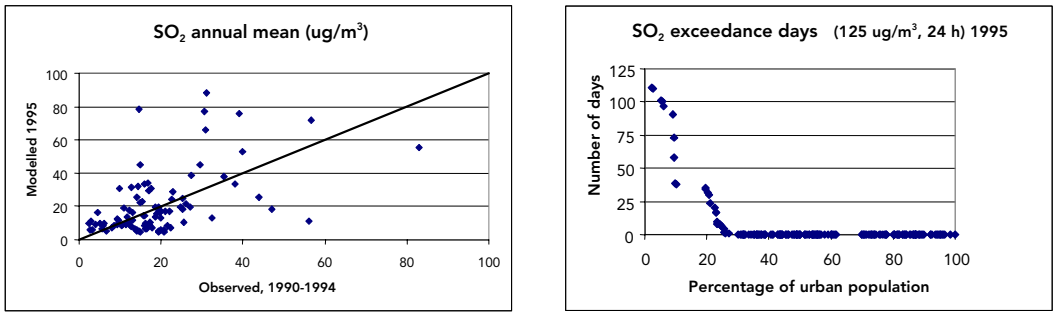


Figure 3.6 presents a comparison between observed and modelled annual mean concentrations. All available annual observations for the period 1990–94 are included and averaged for each site. The modelled concentrations refer to the year 1995, both with respect to emissions and to meteorology. The agreement is reasonable: the RMSE is 16 μg/m³ and 63 % of the data falls within a factor of two.

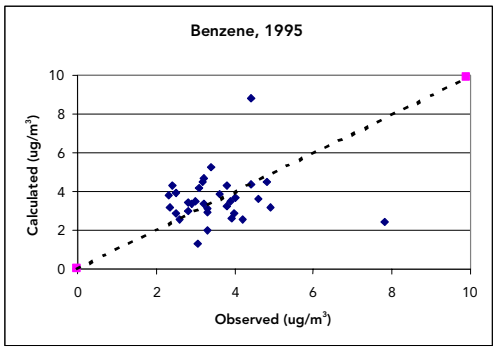
For the reference situation, a frequent violation of both the daily and hourly air-quality objective is noted. Some 25 % of the urban population is exposed more than three times per year to a daily average concentration in excess of 125 μg/m³, see Figure 3.6; for the hourly objective, the percentage of exposed urban population is slightly less (23 %).

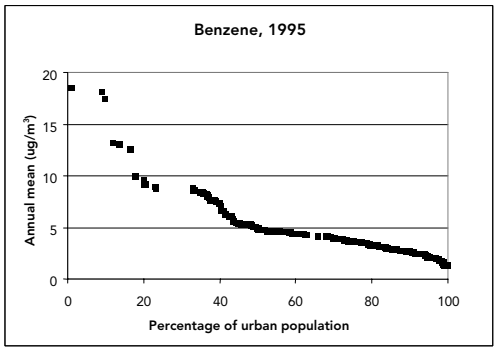
3.6 Benzene: 1995

National emission totals per SNAP sector are taken from Version 5 of the AOP II base case. The comparison with observations is limited partly by the scarcity of data and partly by the fact that measurements are frequently made at stations in a traffic environment. In view of these complications, Figure 3.7 shows a reasonable agreement between modelled and observed concentrations.

The cumulative distribution of annual average benzene concentrations over the populations of the modelled cities is presented in Figure 3.7. About 50 % of the urban population in the modelled cities is exposed to city background levels exceeding the threshold value of 5 μg/m³. High concentrations (as, for example, those calculated for Paris) are largely due to an incidental model artefact: extremely high regional background values were calculated from total emissions, including those from Paris.

Figure 3.7 Left: observed and modelled benzene urban background concentrations; right: cumulative distribution of urban background benzene concentrations over population in modelled cities; reference year 1995





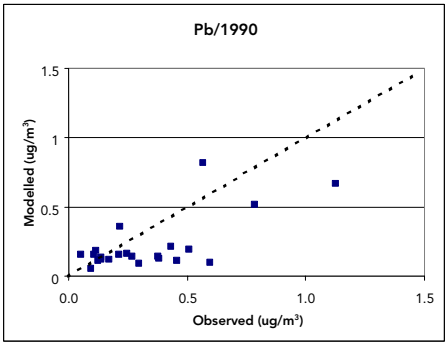
3.7. Lead: 1990

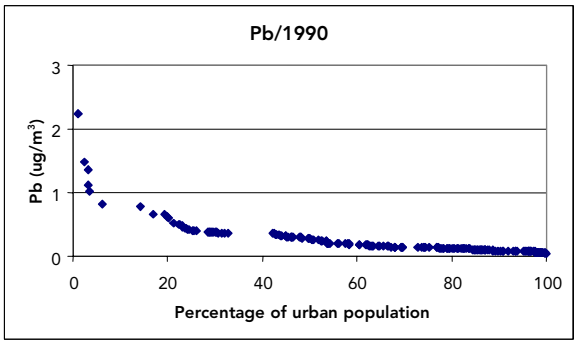
For lead, no information on emissions at SNAP1 level for the individual countries is available for the reference year 1995. The reference calculations have therefore been made for 1990. The modelled concentrations include regional background concentrations obtained by the TREND model.

The comparison with observations (Figure 3.8) is limited by the fact that the measurements are frequently made at stations in a traffic environment. Note that in all calculations, the Spanish emission for SNAP Sector 8 (other mobile sources and machinery) has been corrected (Visschedijk and Smeets, private communication).

Figure 3.8 presents the cumulative distribution of annual mean lead concentrations over the populations of the modelled cities. About 23 % of the urban population in the modelled cities was exposed in 1990 to city background levels exceeding the threshold value of 0.5 •g/m^3.

Figure 3.8. Left: observed versus modelled urban Pb concentrations; right: cumulative distribution of urban background Pb concentrations over population in modelled cities; reference year 1990





3.8. Benzo(a)Pyrene: 1990

Calculations for B(a)P were made for 1990 as information on emissions for 1995 was not available. Under the current assumptions, modelling of the urban background concentrations results in severe exceedances of the threshold: more than 97 % of the urban population is exposed to an urban annual average B(a)P concentration of more than 1 ng/m^3. However, the few available measurements for cities in the UK and the Netherlands indicate that, in the urban background, the B(a)P threshold value is not or only slightly exceeded. In the central parts of the EU, the regional background concentrations already exceed the threshold value of 1 ng/m^3. Only in the periphery of Europe (Greece, Iberian Peninsula, Ireland, Sweden) no exceedances are calculated. However, firm conclusions on B(a)P exposure cannot be drawn from the results of the current study due to major uncertainties in emissions.

The uncertainties in calculated B(a)P concentrations are large. Uncertainties in national emission estimates for PAH range from a factor 2 to 5, mainly because of the uncertainty in data related to domestic (wood) fuel consumption and wood preservation (Berdowski et al., 1997a). Uncertainties in B(a)P national emission estimates are probably no less than those for PAH. Estimation of urban emissions further increases the uncertainty. If, instead of VOC, the NUTS 3 information for one of the other main pollutants is used as a descriptive parameter in the calculations of urban emissions, urban emissions are found to be larger or smaller by a factor of 10. The assumption that residential wood combustion and wood conservation occur only in rural areas adds another factor two to the uncertainties in B(a)P emissions.

4. Projections for base case 2010

In estimating urban emissions for the 2010 base case, an approach similar to the procedure for updating the 1990 emissions to 1995 data was followed, see Equation (1).

$$E_{city,group,2010,X} = E_{city,group,90,X} \times \frac{E_{country,group,2010,X}}{E_{country,group,90,X}} \quad (1)$$

National emissions on SNAP1 level were obtained from SENCO base case Version 5. It should be noted that, in the current procedure, urban emission scenarios simply follow national emission scenarios; specific urban changes in population, built-up areas and in local conditions (e.g. traffic congestion; contribution of traffic emissions to total emissions) are disregarded. If this type of information becomes available for individual cities, emissions can be updated by introducing appropriate adjustment factors.

4.1. Ozone

Figure 4.1 shows the cumulative distribution of the domain average and urban area average number of days with exceedance of the running 8 h average of 120 μg/m^3 ozone in 2010 against the population exposed, presented separately for north and south European cities — calculated with the OFIS model — for meteorological conditions as those of summer 1995. About 15 % of the urban population (two cities) in southern Europe is projected to be exposed to urban ozone levels exceeding the running 8 h average of 120 μg/m^3 ozone on more than 20 days, whereas the number of days with exposure in all cities in northern Europe stays below 20. For the whole of EU-15, 6 % of the urban population is projected to live in non-attainment cities. With regard to the number of days with exceedances averaged over the urban area, the impact of the scenario emission reductions appears to be significant for all European cities under consideration: the model projections show no exceedance of the target value on more than 20 days.

Figure 4.2 shows scatter plots of the year 2010 against the year 1995 calculated number of days with the running 8 h mean exceeding 120 μg/m^3, and 6-month average ozone concentrations for all urban areas. The results show that for the majority of the cities, the days of exceedances as well as the maximum ozone concentrations (not shown) are reduced considerably from 1995 to 2010. Not surprisingly, the emission reductions appear to lead to higher summer average ozone concentrations in most cities since, under conditions with lower NO_x emissions, there will be a shift in the photostationary equilibrium in favour of more ozone.

Figure 4.1. Cumulative distribution of days with exceedance of the running 8 h average of 120 μg/m³ ozone (base case 2010) over the population in the modelled cities in northern Europe (circles) and cities in southern Europe (triangles); left: maximum in the urban area; right: average over the urban area; the bold lines in the figures refer to the proposal for the 2010 limit value

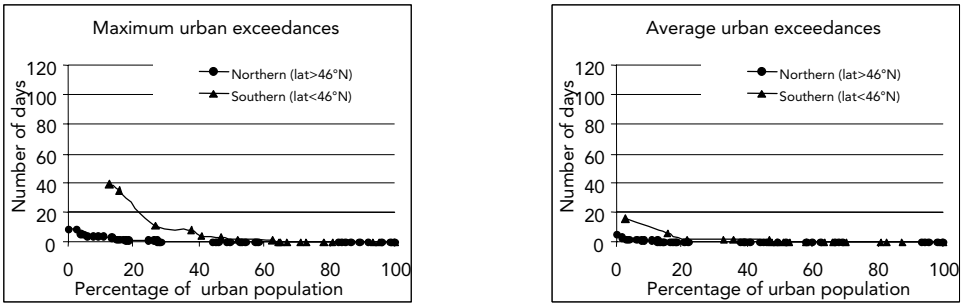
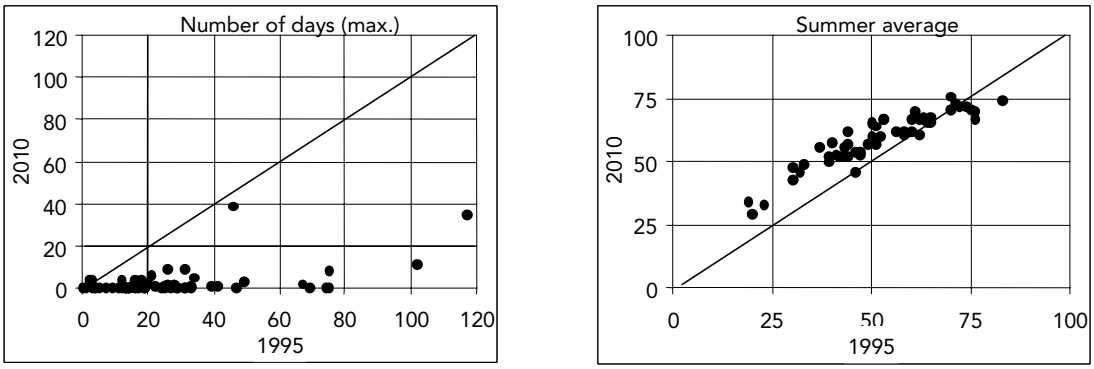


Figure 4.2. OFIS model results (base case 2010) for the days with the running 8 h mean exceeding 120 μg/m³ (left), and the summer average (right) ozone concentrations compared to the reference year 1995; the bold lines in the figures refer to the air-quality objectives



4.2. Nitrogen dioxide

4.2.1. cQ model

Future urban annual averages of NO_2 were calculated by the cQ model for cities with sufficient reported monitoring data. Nitrogen dioxide is related to emissions of nitrogen oxides directly using an empirical conversion to nitrogen oxides (DGXI, 1996). This approach is discussed in detail in CEC (1998).

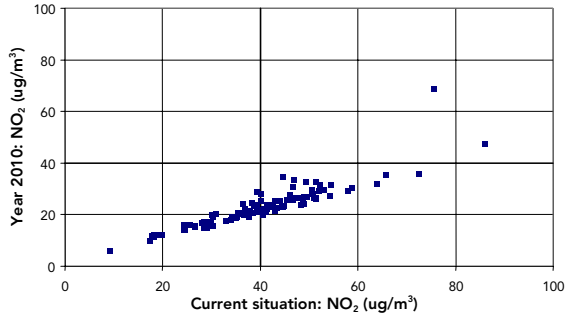
The cQ model is based on annual averages. The conversion factors applied to expand the measurement database of annual averages and to characterise short-term concentrations (CEC, 1998) are given in Table 4.1. The source of the conversion factor for maximum hourly value is the Auto-Oil I study (DGXI, 1996). The environmental objectives in this study are given for hourly values (200 μg/m³ not to be exceeded more than 18 times a year, i.e. 99.8th percentile), and for annual average concentration (40 μg/m³).

Table 4.1. Conversion factors between annual average and short-term characteristics for NO_2; the conversion factor for maximum hourly value was derived in the Auto-Oil I study

Reported annual statistics: NO_2	Average ratios *a*: annual average = *a* * annual statistics	Number of site-years used for derivation of *a*	Standard error of *a*
50th percentile of hourly values	1.06	580	$2.9 * 10^{-3}$
98th percentile of hourly values	0.43	627	$2.5 * 10^{-3}$
Maximum hourly value	0.19	not available	not available

The annual average objective is projected to be attained in 2010 in all cities except two (see Figure 4.3), representing 5 % of the population. This result is robust under a sensitivity analysis with conversion factors derived from empirical data.

Figure 4.3. Current (1995) and projected (2010) annual averages for nitrogen dioxide



4.2.2. UAQAM

Urban concentrations for 2010 were calculated for all selected cities. There is a large reduction in urban NO_2 concentration in the projections. Still, for about 19 % of the urban population, the mean value is in excess of the air-quality objective for 2010 (in 1995: 65 %). Here, a discrepancy with the cQ model was found; further work is needed to resolve these differences. A better agreement between the two models is obtained for exceedances of the hourly air-quality objective. According to UAQAM projections, exceedances of an hourly NO_2 concentration of 200 $\mu g/m^3$ are to be expected in one or two cities. The number of exceedances is, however, less than 18; the objective for hourly NO_2 concentrations is therefore attained in all cities in these projections.

4.3. Fine particulates (PM_{10})

4.3.1. cQ model

Future urban annual averages of PM_{10} were calculated with the cQ model for cities with sufficient reported monitoring data. The conversion factors between different statistics for PM_{10}, derived from the measurement database, are summarised in Table 4.2 (CEC, 1998). The factors can be applied to characterise short-term concentrations and environmental objectives.

Table 4.2. Conversion factors between annual average and short-term characteristics for PM_{10}

Reported annual statistics: PM_{10}	Average ratio *a*: annual average = *a* * annual statistics	Number of site-years used for derivation of *a*	Standard error of *a*
50th percentile of daily values	1.14	88	$9.4 * 10^{-3}$
98th percentile of daily values	0.4	134	$8.7 * 10^{-3}$
Maximum daily value	0.28	79	$10.6 * 10^{-3}$

According to these conversion factors, the two objectives for particulate matter in this study (50 µg/m^3 as daily average 98th percentile and an annual average of 20 µg/m^3) are fully equivalent. In 2010, the annual averaged concentrations are calculated to be about 20 % lower than current levels (see Figure 4.4). The environmental objectives are estimated to be exceeded for 62 % of the population covered by the database.

4.3.2 UAQAM

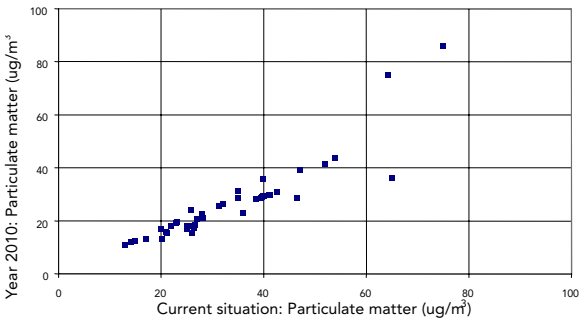
Urban PM_{10} concentrations for 2010 were calculated by UAQAM for all selected cities using emissions based on Version 4 as well as Version 5 of the base case scenario. An overview of the fraction of the urban population living in cities where the objectives are expected to be exceeded is presented in Table 4.3. In evaluating the objective for annual average PM_{10} concentrations, a contribution from sea salt (Eerens et al., 1998) was included. There is a reasonable agreement with the results of the cQ model.

Table 4.3. Fraction (in %) of urban population living in non-attainment cities

Year	Objective annual ([1])	Daily
1995, Version 4	82/93	94
2010, Version 4	60/85	71
1995, Version 5	70/87	89
2010, Version 5	39/52	71

([1]) Fraction respectively without and with correction for sea salt.

Figure 4.4. Current (reference year 1995) and projected (2010) annual averages for particulate matter



4.4 Carbon monoxide

The base case emissions for CO were obtained from Version 5. Background concentrations were simulated by a log-normal distribution (see Section 2.4).

Under these assumptions, the UAQAM calculations indicate that some exceedances of the 10 mg/m^3 level are still to be expected in 2010. Depending on the meteorological conditions, the number of cities with exceedances ranges from two (0.5 % of the total modelled population) to six (1.5 % of the population). The population exposure above threshold ([1]) varies between $1.1 \cdot 10^6$ and $2.3 \cdot 10^7$ person·mg/m^3; with respect to 1995, this is a reduction by a factor of 10 or more. Again, exceedances are only modelled for south European cities. The regional background concentrations are based on rather conservative assumptions. When lower background concentrations are assumed, some, but not all, exceedances will be eliminated since, for some cities, the modelled maximum 8 h concentration is just above the threshold value (ranging from 10.2 to 15.7 mg/m^3).

4.5 Sulphur dioxide

4.5.1. cQ model

Future urban annual averages of SO_2 were calculated by the cQ model for cities with sufficient data. Statistical conversion factors were applied to expand the measurement database of annual averages (in cases where only other statistics were reported), and to characterise short-term concentrations (CEC, 1998). The environmental objectives for SO_2 in this study are 350 µg/m^3 as a 99.7th percentile for hourly values (not more than 24 exceedances per year), and 125 µg/m^3 as a 99.2th percentile of daily concentrations (not more than three exceedances per year). The conversion factors for SO_2 statistics are given in Table 4.4.

Table 4.4. Conversion factors between annual average and short-term characteristics for SO_2

Reported annual statistics: **SO_2**	Average ratios *a* and *b*: Annual average = *a* * annual statistics; annual statistics = *b* * annual average	Number of site-years used for derivation of *a*	Standard error of *a* or .
50th percentile of daily values	*a* = 1.23	745	$7.5 * 10^{-3}$
98th percentile of daily values	*a* = 0.28	823	$3.1 * 10^{-3}$
maximum daily value	*a* = 0.15	761	$2.9 * 10^{-3}$
99.7th percentile of hourly values	*b* = 9.1	79	2.46
99.2th percentile of daily values	*b* = 4.8	74	1.46

The annual average concentrations are projected to be reduced in all cities between 1995 and 2010 (see Figure 4.5). The environmental objective for hourly values corresponds to an annual average of 38 µg/m^3, which is exceeded in only one city representing 2 % of the population. The environmental objective for

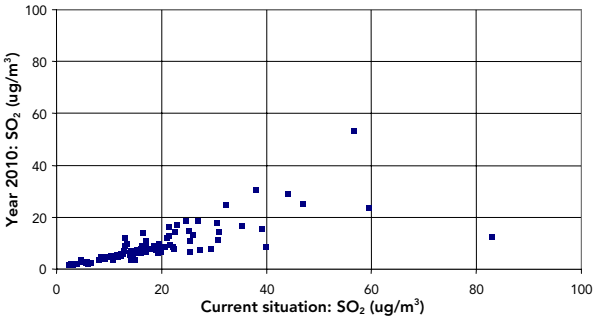
([1]) For evaluating the extent of exceedance of environmental objectives, the population exposure above a threshold (PET) is defined as:

$$PET = \sum_{n=1}^{N_{city}} \sum_{i=1}^{E_n} \left(C_{i,n} - T\right) pop_n$$

where $C_{i,n}$ is the concentration in excess of the threshold value T in city *n* during exceedance *i*; N_{city} the number of cities where an exceedance is calculated; E_n is the number of exceedances; and pop_n is the population of city *n*. PET is expressed in persons.µg/m^3.

daily values corresponds to an annual average of 26 μg/m^3 and is exceeded for 7 % of the population. Industrial hot spots are not taken account of in the calculations, so it cannot be ruled out that there are areas of higher SO_2 concentrations within the cities of the database.

Figure 4.5. Current (reference year 1995) and projected (2010) annual average concentrations of sulphur dioxide



4.5.2 UAQAM

There is a large reduction in urban SO_2 concentrations calculated by UAQAM for 2010. The air-quality objective for the daily averages is exceeded in nine cities (11 % of the population). For a meteorologically more favourable year, 1990, 9 % of the population will be exposed in the 2010 projections.

Results for Athens and Thessaloniki, suggesting frequent exceedances, however, are likely to be wrong ([2]).

The objective for hourly concentrations is exceeded in four cities (6 % of the population); again the two Greek cities show a high number of exceedances. Exceedances of this objective strongly depend on the meteorological conditions: using meteorological data of 1990 results in projected exceedance in only two cities (3 % of the population).

There is a fair agreement between the forecasts of the cQ model and UAQAM: 7 % versus 9–11 % of the population for the daily objective and 2 % versus 3–6 % of the population for the hourly objective.

4.6. Benzene

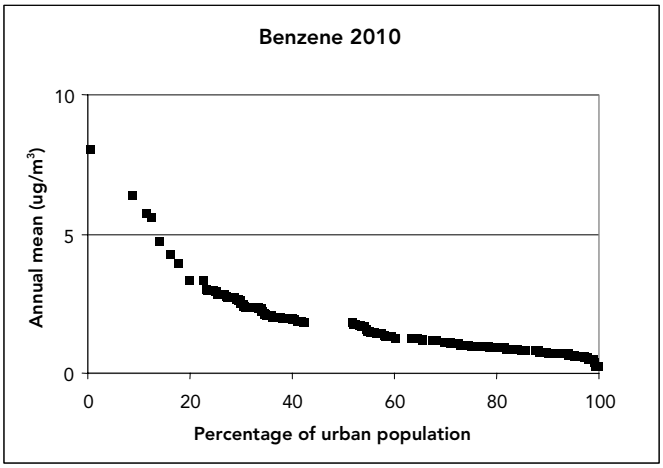
For 2010, emissions for benzene were taken from the AOP II base case, Version 5. The difference between the two versions is mainly in traffic emissions which have a relatively strong impact on urban air quality. The regional background concentrations are obtained by applying a uniform reduction on the TREND calculations for 1995 according to the overall emission reduction in EU-15.

([2]) A frequent violation during more than 100 days is projected for both Greek cities in the selection for this study, Athens and Thessaloniki. These results are most likely to be wrong. Although the total Greek emissions reduce by more than 60 % between 1995 and 2010 (from 1519 to 541 ktonne/year), the urban emissions increase by about 50 %. The reasons for this difference is that the national reduction is mainly in SNAP Sector 1 (large combustion plants) which is unimportant for both cities whereas emissions by other mobile sources (SNAP Sector 8), which makes a large contribution to the urban emissions, increase strongly (by more than a factor of 2). The Greek submission to Corinair includes emissions from total marine bunker fuel purchased by sea vessels in Greece. The NUTS 3 allocation of emissions from other mobile sources in Athens and Thessaloniki is probably an overestimation, as only a fraction of the fuel will be used in the direct surroundings of the city.

The model calculations indicate (see Figure 4.6) that in four cities (about 13 % of population in the selected cities) the urban background concentrations will still be in excess of the threshold value of 5 μg/m^3. Not only is the number of people exposed strongly reduced, but so is the exposure level. In 1995, the population-weighted average concentration in cities in excess of the threshold is 10.5 μg/m^3; for 2010, a value of 6.3 μg/m^3 is calculated.

The highest benzene concentration was calculated for Paris. It is most likely that the model overpredicts the concentration due to an overestimation of background levels (see above).

Figure 4.6. Cumulative distribution of urban background benzene concentrations over population in modelled cities; reference year 2010



4.7 Lead

Base case emissions for lead are not included in the SENCO database; here the policy in place (PIP) estimates from the European priority study (Visschedijk et al., 1999) were used. The background concentrations were obtained from TREND calculations (Hammingh, personal communication) using the same PIP emission data. It should be noted that the emission reductions in non-EU countries have been included in these background calculations.

The model calculations indicate that, in 2010, the urban background levels are expected to exceed the threshold value of 0.5 μg/m$^{3\,in}$ in none of the modelled cities. A similar conclusion is reached when the urban emissions are estimated following the top-down approach.

4.8 Benzo(a)Pyrene

As discussed above, the calculations for B(a)P are too uncertain to derive any firm conclusion for the reference situation. An outlook for urban B(a)P concentrations can therefore not be given. However, if one assumes that the derived policy in place emissions for 2010 (Visschedijk et al, 1999) are, at least in a qualitative way, indicative of the future development of B(a)P emissions, an improvement of B(a)P urban air quality is not to be expected.

5. Discussion

An overview of the results obtained by the various models for the reference year 1995 and projections for 2010 is presented in Table 5.1.

The calculated results for the reference year were compared to measured air-quality data. The comparison of modelled and measured air quality is limited by a lack of (reliable) data. The air-quality database, Airbase, has proved to be a valuable tool but needs further input of air concentration data from Member States. Despite all uncertainties, the modelled air quality is in acceptable agreement with the observations.

The baseline projected emissions for 2010 result in a large improvement in urban air quality. However, exceedances of several environmental objectives are still to be expected. Results for B(a)P are not included in Table 5.1; these results are highly uncertain and no firm conclusion can be made. The objectives for PM_{10}, both short-term and long-term, as well as the NO_2 long-term objectives are projected to be exceeded most frequently in 2010.

Figure 5.1 shows that a large part of the population is simultaneously exposed to above-threshold concentrations of several pollutants. For instance, in 1995, about 25 million inhabitants lived in cities where the objectives for four pollutants were exceeded simultaneously; for more than 40 million inhabitants, concentrations of four or more were above the objectives. In 2010, this number will be reduced to less than 4.5 million according to the projections made in this study.

Urban air quality not only improves in terms of population exposed but also in terms of severity of the exposure. Using the population exposure above a threshold as defined in Chapter 4, the changes in population exposure are presented in Figure 5.2. The figure shows that the PET-values are reduced by at least a factor of 2. Table 5.1 indicates that for PM_{10} there is a limited reduction in the total population living in non-attainment areas. For the population at risk there is, however, a large reduction in exposure.

Table 5.1. Fraction (in %) of total urban population living in non- attainment cities; environmental objectives are defined in Table 1.1

Pollutant	Averaging period	1995 ([1]) observed	1995 ([2]) UAQAM /OFIS	2010([3]) cQ	2010([2]) UAQAM /OFIS
SO_2	1 hour	14 %	23 %	2 %	3-6 %
SO_2	24 hours	38 %	25 %	7 %	9-11 %
NO_2	1 hour	77 %	5 %	5 %	0 %
NO_2	calendar year	73 %	64 %	5 %	19 %
PM_{10}	24 hours	97 %	89 %	62 %	71 %
PM_{10}	calendar year	97 %	87 % ([4])	62 %	52 % ([4])
CO	8 hours		11 %	-	0.5-1.5 %
O_3	daily 8 h max		48 %	-	6 %
Benzene	calendar year		50 %	-	12 %
Pb	calendar year		23 % ([5])	-	0 %

([1]) Fraction estimated from monitoring data. Note that monitoring data are not available for the full set of 192 conurbations.
([2]) Fraction estimated from UAQAM and OFIS (ozone only) model calculations.
([3]) Fraction estimated from cQ model calculations.
([4]) UAQAM estimates for PM_{10} include sea salt contribution.
([5]) Reference year for Pb model calculations is 1990.

Figure 5.1. Urban population simultaneously exposed to concentrations of the pollutants CO, NO_2, SO_2, PM_{10}, benzene or Pb in excess of the air-quality objectives

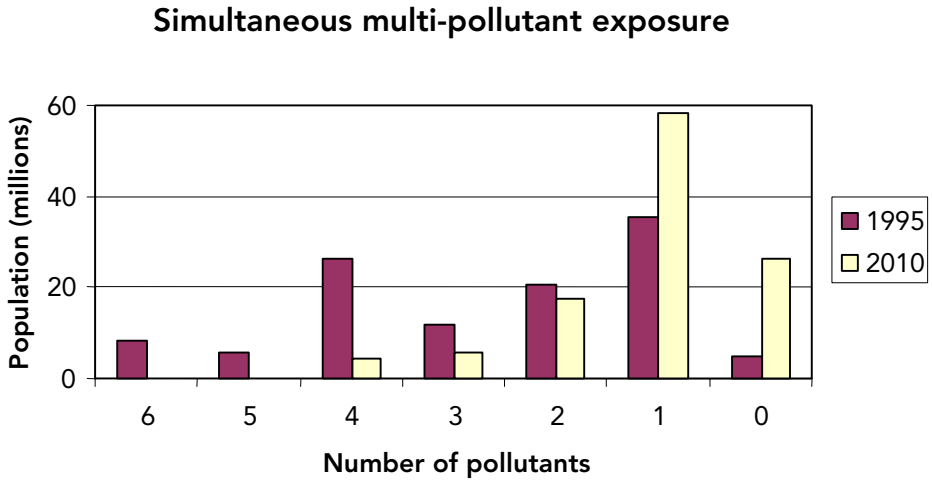


Figure 5.2. Relative changes in population exposure (expressed as PET) for various emission scenarios; the situation in the reference year 1995 is set to unity; air-quality objectives are given in Table 1.1

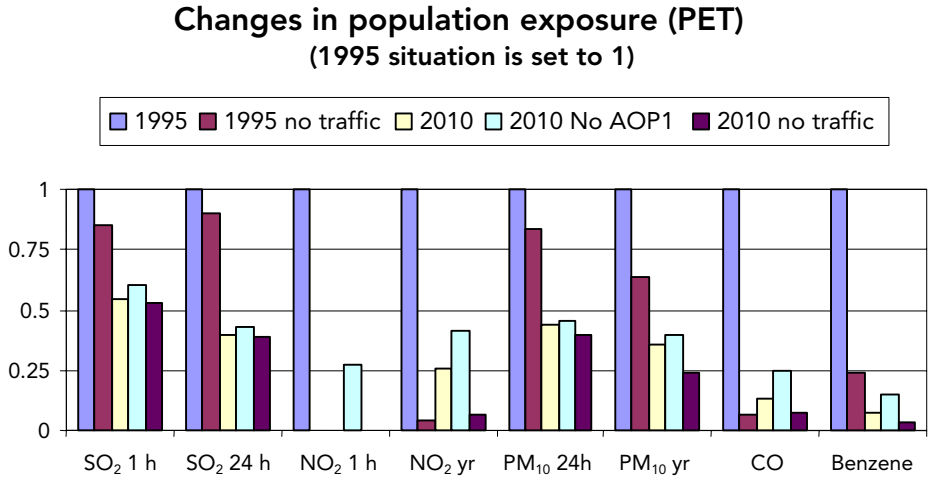


Figure 5.2 also shows the results for a 2010 scenario assuming that the emission reduction measures as defined in the Auto Oil I directives have not been implemented (indicated as 'no AOPI'). In this scenario, emissions for all other categories were taken as equal to the 2010 base case scenario. Comparison of this scenario with the base case situation for 2010 shows the benefits of the Auto-Oil I directives. Large effects are seen for NO_2, CO and benzene; for SO_2 and PM_{10} the impact of the AOP-I directives is much smaller; for these pollutants other source categories and/or the long-range contributions are more important. This is further illustrated in the sensitivity calculation in which all emissions for road transport have been set to zero (indicated as 'no traffic'). Note that even in this hypothetical no-traffic situation there are still exceedances of the air-quality objectives. Reaching all objectives will only be possible when further abatement measures for other source categories are introduced.

6. Comparison with detailed modelling results

The urban impact assessment coordinated by the Environment Institute of the Joint Research Centre (JRC) concentrated on the detailed examination of air quality in the 10 selected AOP II-cities. Model calculations were performed with a high spatial resolution (about 2 x 2 km) for a period of three to five days. Two periods were selected for the calculations; based on measured 1995 air-quality data, a period with the smallest deviation from the annual mean concentration was chosen as the best period to represent the annual mean conditions. For each city, one period was selected as representative for an annual mean period for the pollutants benzene, CO and NO_2. For the simulation of exceedances of hourly or daily threshold values, a period was selected in which the measured maximum hourly concentration was close to the hourly 98th percentile limit value for CO or NO_2; for PM and benzene, the same period was selected. The periods selected were different for the 10 cities.

A direct comparison between the two methods is difficult as the results have a complementary character. The JRC results have a high spatial resolution but the (surrogate) annual average is based on a limited number of hours. The GEA calculates a city-averaged concentration, but the annual average is based on all hours of the year. Furthermore, the representativeness of the observed data are not always clear. On a pollutant-by-pollutant basis, results of the two approaches are inter-compared below and also compared with observations, with the purpose of seeing whether the two methods corroborate the conclusions on urban exceedances in the EU in 1995 and 2010.

Nitrogen dioxide
In view of the availability of measured data, NO_2 results are discussed here in more detail. In Figure 6.1 and Table 6.1, a comparison between the results of both approaches in modelling the annual average NO_2 concentrations is presented. The full lines in Figure 6.1 give the 1995 and 2010 results using the UAQAM ; the cities are ranked according to the 2010 concentration. The variations in the 1995 line illustrate that the impact of the 2010 emission scenario differs from one city to the other. The highest annual mean concentrations calculated in the JRC approach over the city domain (resolution about 2 x 2 km, all data are taken from the draft report (Version 5.0) for the AOP II Contact Group, November 1999) are presented as squares (1995) and triangles (2010). The observed concentrations (period 1992–96) are given as asterisks.

Because of the high spatial resolution, one expects that the maximum concentration from the JRC approach exceeds the city-averaged values of UAQAM in all cases. Generally, this is the case, but even this simple comparison is hampered: the location of the JRC maximum might fall outside the city domain of the UAQAM calculations. This is for example seen in Utrecht; here the maximum concentrations, according to the JRC model, are located in the Amsterdam agglomeration. Striking differences between the two approaches are found for Madrid, Köln and Helsinki. For these cities UAQAM prediction are substantially higher than the JRC results. The observations in Madrid and Helsinki suggest that the JRC underestimates the annual mean in these cities. UAQAM most likely overestimated the concentrations in Köln.

In Table 6.1, the comparison is more directed to exceedances of the threshold value of 40 µg/m^3. For the JRC results, the spatial extent of the exceedance over the city domain is presented in a simple way. For the UAQAM results, the excess of the concentration over the threshold is indicated. One may safely assume that the spatial extent of an exceedance will increase with increasing concentrations. The actual relation between exceedance area and excess concentration will depend on local conditions; the conclusion that an x % excess concentration results in an exceedance area of x % which might be suggested by Table 6.1, is incorrect.

Figure 6.1. Comparison of modelled NO_2 annual mean concentrations; upper line corresponds to the 1995 results, lower line to the 2010 results from the UAQAM ; squares and triangles correspond to the maximum concentration in the urban domain, calculated by the JRC for 1995 and 2010, respectively; asterisks indicate observed annual means (1992–96); note that Amsterdam has been included in this figure as the JRC calculations for Utrecht indicated that the maximum concentrations are located in the Amsterdam agglomeration and not in the selected inner urban domain of Utrecht

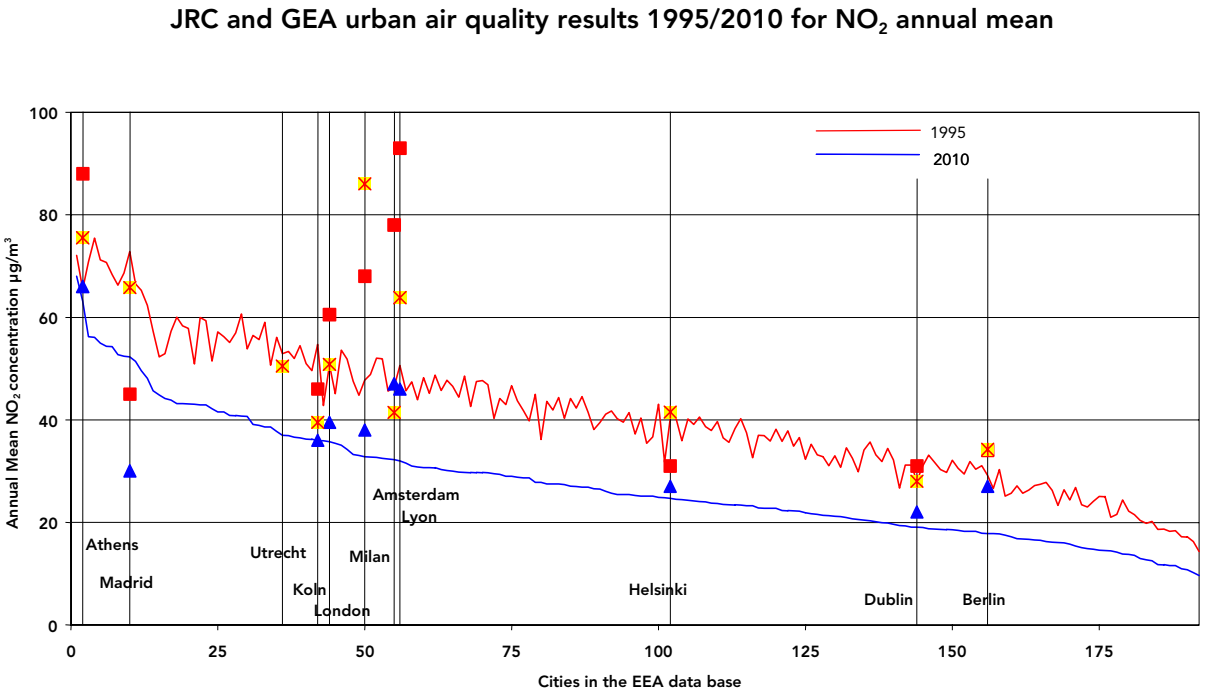


Table 6.1. Comparison between modelled annual mean NO_2 concentrations

NO_2 annual mean	JRC		GEA		Obs.
	1995	2010	1995	2010	1992–96
Athens	●●●●	●●●●	●●●	●●●	●●●●
Berlin	❍	❍	❍	❍	❍
Köln	●●●●	❍	●●	❍	❍
Dublin	❍	❍	❍	❍	❍
Helsinki	❍	❍	●	❍	●
London	●●	❍	●●	❍	●●
Lyon	●●●	●	●●	❍	●●●
Madrid	●	❍	●●●●	●●	●●●
Milan	●	❍	●	❍	●●●●
Utrecht	❍	❍	●●	❍	●●

Legend to the table:

In JRC calculation, the geographical extent of an exceedance is indicated as follows:
- ❍: no exceedance in the city;
- ●: exceedance in 0–25 % of the city area;
- ●●: exceedance in 25–50 % of the city area;
- ●●●: exceedance in 50–75 % of the city area;
- ●●●●: exceedance in 75–100 % of the city area.

In GEA calculation and observations, the concentration is indicated as follows:
- ❍: no exceedance in the city (concentration below threshold);
- ●: concentration 0–25 % above threshold;
- ●●: concentration 25–50 % above threshold;
- ●●●: concentration 50–75 % above threshold;
- ●●●●: concentration more than 75 % above threshold.

Evaluating both approaches on exceedances of the threshold value for annual average NO_2 concentrations reveals different conclusions for Helsinki and Utrecht for 1995: for both cities, the GEA as well as observations indicate an exceedance; according to the JRC calculations, these cities are in compliance. For Madrid, the JRC estimates an area of exceedance of 3 % whereas the GEA predicts a concentration which is about 80 % above the threshold. Measurements in Madrid are about 60 % above the threshold. For 2010, different conclusions are reached for Lyon (an exceedance area of 9 % according to the JRC but compliance according to the GEA) and again Madrid. Both approaches calculate a decrease in concentrations of 30–35 % for Madrid, but in the GEA calculations, the annual average concentration still remains above the threshold.

Table 6.1 shows that for 1995, the GEA indicates more cities to be in exceedance than the JRC analysis. Given the exceedance areas and assuming a population density to be constant throughout the urban domain, it is estimated for 2010 that 12 % of the population in the 10 AOP II cities is exposed to an annual NO_2 concentration above the threshold. The GEA gives a higher estimate (19 %), but this number refers to the population in the GEA set of 192 cities.

With respect to exceedances of the short-term objective for NO_2, both methods conclude that this objective will be attained in all cities in 2010.

Benzene

Similar graphs can be made for comparison of annual average concentrations of benzene (Figure 6.2, Table 6.2). For the reference year 1995, a comparison of the

JRC maximum and GEA city-averaged concentrations shows inconsistencies for Madrid, London and Helsinki. For these three cities, the GEA city-averaged concentration exceeds the JRC maximum. There are insufficient monitoring data to test both model predictions.

Furthermore, the JRC approach predicts substantial exceedances in Berlin (in 52 % of the area) whereas the GEA predicts a concentration just below the threshold (4.2 µg/m^3); the observations in Berlin indicate an annual average of 3.1 µg/m^3. In 2010, the JRC modelling approach predicts limited exceedances (1–2 % of the city area) in Athens, Lyon and Milan; the exceedance in Athens is confirmed by the GEA but it predicts concentrations in Lyon and Milan, which are well below the threshold (2.4–2.7 µg/m^3).

According to the JRC approach, in 2010, less than 0.5 % of the population in the 10 AOP II cities is exposed to benzene concentrations above the threshold. The GEA estimates exceedances in four out of the 192 GEA cities where 12 % of the population is living. If the results for Paris, where concentrations are most likely overestimates (see the discussion above) are excluded, 4 % is found to be exposed to concentrations above the threshold.

Figure 6.2. Comparison of modelled benzene annual mean concentrations; the upper line corresponds to the 1995 results, lower line to the 2010 results from the UAQAM ; squares and triangles correspond to the maximum concentration in the urban domain, calculated by the JRC for 1995 and 2010, respectively; asterisks indicate observed annual means (1992–96); note that Amsterdam has been included in this figure as the JRC calculations for Utrecht indicated that the maximum concentrations are located in the Amsterdam agglomeration and not in the selected inner urban domain of Utrecht

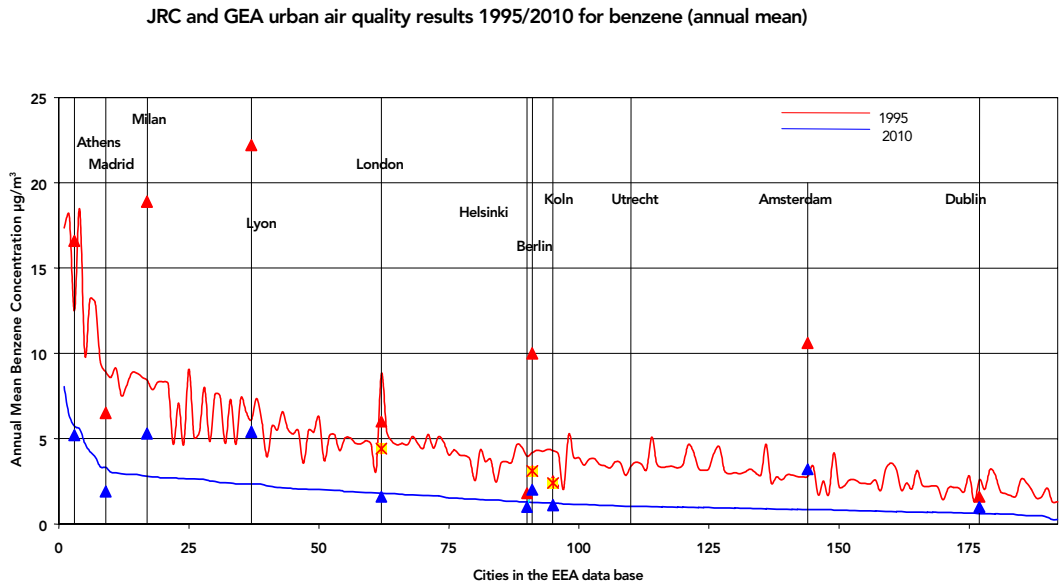


Table 6.2. Comparison between modelled annual mean benzene concentrations

Benzene annual mean	JRC		GEA		Obs.
	1995	2010	1995	2010	1992–96
Athens	●●●	●	●●●●	●	-
Berlin	●●	❍	❍	❍	❍
Köln	❍	❍	❍	❍	❍
Dublin	❍	❍	❍	❍	-
Helsinki	❍	❍	❍	❍	-
London	●	❍	●●●●	❍	❍
Lyon	●●	●	●	❍	-
Madrid	●	❍	●●●●	❍	-
Milan	●●	●	●●●	❍	-
Utrecht	❍	❍	❍	❍	-

Legend to the Table:
In JRC calculation, the geographical extent of an exceedance is indicated as follows:

❍: no exceedance in the city;
●: exceedance in 0–25 % of the city area;
●●: exceedance in 25–50 % of the city area;
●●●: exceedance in 50–75 % of the city area;
●●●●: exceedance in 75–100 % of the city area.

In GEA calculation and observations, the concentration is indicated as follows:

❍: no exceedance in the city (concentration below threshold);
●: concentration 0–25 % above threshold;
●●: concentration 25–50 % above threshold;
●●●: concentration 50–75 % above threshold;
●●●●: concentration more than 75 % above threshold.

Carbon monoxide

A direct comparison of CO concentrations is not possible due to the differences in time averaging (8 h maximum versus annual mean) but a comparison of compliance with CO standard has been made. In 1995, the south European cities, Athens, Lyon and Milan, have an exceedance area of 6–24 % following the JRC calculations. The GEA also predicts exceedances in south European cities. However, out of the 10 AOP II cities, only for Madrid is a breach of the CO threshold calculated. For 2010, there is an excellent correspondence: no exceedances are predicted in the 10 cities by both approaches.

Fine particulates PM_{10}

PM_{10} comparison is hardly possible, since different components have been modelled in the two studies. In the JRC approach, only the primary emitted fraction has been considered, whereas in the primary and secondary GEA, aerosol are accounted for. The JRC results suggest that around half of the 10 AOP II cities would exceed the annual average objective of 20 $\mu g/m^3$ in 2010; the GEA indicates that more than 50 % of the population living in the cities modelled by the GEA is exposed to above-threshold concentrations. Although there are large uncertainties in the emission estimates and PM_{10} results must therefore be seen as tentative. Both studies clearly indicate that PM_{10} exposure is presently and in the next decade one of the major issues in urban air quality.

Ozone

Reporting of the JRC simulations of urban ozone had not been finalised at the time of writing of this report.

7. Conclusions

In the current (1995) situation, a large fraction of the urban population is exposed to concentrations of one or more pollutants which are in excess of the air-quality objectives set for the year 2010. The current study indicates that the situation will be much improved in 2010 under the AOP II base case scenario but a full compliance with all the objectives is not expected. Full compliance can only be realised by means of additional reductions for source categories other than road transport. However, especially for NO_2, CO, and benzene there are clear benefits from the Auto-Oil I directives.

The generalised empirical approach (GEA) is a simple modelling methodology by which the urban air quality in a large number of cities can be evaluated for a range of pollutants.

The top-down GEA to estimating urban emissions from national totals may not accurately reflect the actual situation in every city considered but comparison with emission data otherwise obtained from inventories nevertheless indicates that the approach is reasonably robust. Further work on estimation of urban emissions is needed to reduce uncertainties.

Despite all uncertainties, the modelled air quality for the reference year is in acceptable agreement with the available observations. The comparison of modelled and measured air quality is limited by a lack of (reliable) data. The air-quality database Airbase has proved to be a valuable tool but needs further input of air-quality data from Member States.

Results from the GEA were compared with the urban impact assessment carried out by the JRC in the Auto-Oil II air-quality study. The JRC used state-of-the-art modelling techniques and ultra-high resolution urban emission inventory results. The results of the two studies, although sometimes quite different for specific cities and pollutants, lead to largely similar conclusions with regard to exceedances in 2010.

This study has demonstrated that the GEA can provide relevant information for those concerned with framing and implementing environmental policies at the European level.

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Annex 1: Methods and input data

A1. Selection of cities and data collection

A1.1. Selection of cities

Since the Auto-Oil programme aims at the development of traffic-related air-quality improvement measures, no attempts have been made to include all cities where exceedances might occur due to industrial emissions (industrial hot spots). Selection criteria were size (all conurbations with more than 250 000 inhabitants) and availability of air-quality monitoring data.

From lists of human settlements with more than 50 000 inhabitants in Europe obtained from WHO-ECEH, Bilthoven, and from the UN Statistical Division (UN, 1997), all cities in the EU-15 Member States with more than 250 000 inhabitants (120 cities) were selected. This list of 120 cities has been extended with a number of smaller cities (about 50) with reliable monitoring data based on a recent update of Airbase (EEA, 1999). Availability of CO data was disregarded in the selection of cities, since exceedances of air-quality objectives for this pollutant were not expected.

Table A1. Total population, urban population (EEA, 1998) and total population in selected cities and the fraction of urban population of the total urban population in each Member State; population numbers are given in 1 000s.

Country	Total	Urban	Selected (1)	% (3)	Selected (2)
Austria	8 045	5 176	2 332	45	1 778
Belgium	10 128	9 823	2 763	28	1 628
Denmark	5 224	4 451	2 043	46	500
Finland	5 106	3 225	1 268	39	1 016
France	58 103	43 385	21 368	49	14 975
Germany	81 594	70 575	21 272	30	11 192
Greece	10 453	6 193	3 822	62	3 822
Ireland	3 546	2 039	916	45	916
Italy	57 205	38 113	11 020	29	6 730
Luxembourg	407	363	76	21	76
Netherlands	15 482	13 775	5 034	37	2 803
Portugal	9 815	3 493	2 936	84	2 832
Spain	39 627	30 297	11 030	36	6 152
Sweden	8 788	7 303	2 111	29	1 325
United Kingdom	58 079	51 821	24 624	48	20 545
EU-15	371 602	290 032	112 614	39	76 290

(1) Population in cities selected for inert species calculations.
(2) Population in cities selected for ozone calculations.
(3) Percentage of urban population in selected cities relative to total urban population (column 3).

The selected cities are presented in Map 1 and listed in Annex 2. In Table A1 and Figure A1, some statistical information on selected cities is presented.

The calculations of ozone concentrations were carried out for a sub-set of 57 cities, including almost all cities with more than 0.5 million inhabitants, see Figure A1. The 10 cities analysed in the urban impact assessment (Athens, Berlin, Köln, Dublin, London, Lyon, Helsinki, Madrid, Milan/Reggio Emilia, Utrecht) are included in the selection.

Table A1 gives an overview of the total population in the selected cities for each of the Member States. Data on total and urban population in the Member States is from the EEA (1998). The selected cities cover almost 40 % of the EU urban population. On a country basis, the 57 cities selected for the ozone calculations represent 55–100 % of the population in cities selected for inert pollutant modelling.

A1.2. Estimation of urban area

For each city the size of the urban area was estimated by ETC on Land Cover (ETC/LC, Robert Enesund, private communication, 1998) by a procedure described in ETC/LC (1997). Basic input is the Corine land cover data set and the 'Major land cover types of Europe' (MLCT) data set. The MLCT data set is used here, since Corine data are unavailable for some countries. In the evaluation of area, typical urban land cover classes are considered. When urban polygons are less than 200 metres apart, they are assumed to be from the same urban agglomeration. The distance between some cities is so small that, under this procedure, some cities merge into urban agglomerations.

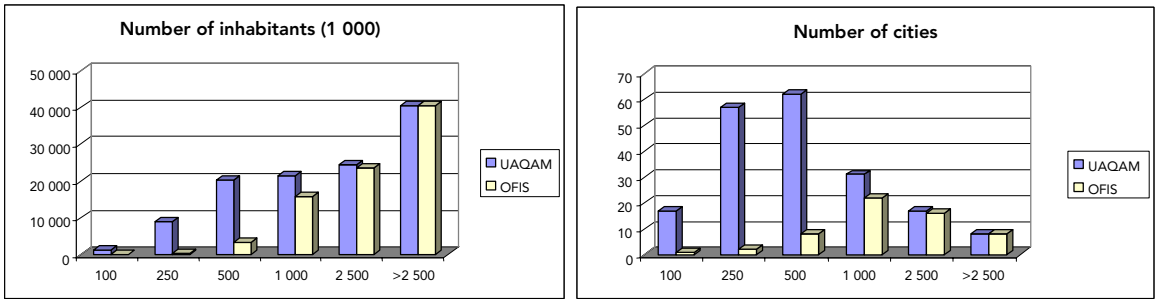
The procedure failed to produce a meaningful result for Helsinki, a city that is highly fragmented. The urban area of the Helsinki agglomeration was set at 242 km^2 (Sluyter, 1995).

The size of the built-up area is a critical parameter in air-quality modelling which is difficult to validate. Correlation between the Corine and the MLCT-based estimates of urban area is good, but the MLCT estimates are systematically 25–30 % larger.

Population densities were calculated and analysed. For Murcia (Spain) and Braunschweig (Germany), some obvious data errors were found, and urban area data were corrected.

In comparison to other estimates (e.g. Sluyter, 1995), the population densities used in the present study appear to be relatively high, with a large scatter. Since population data are in reasonable agreement between the two studies, the urban area estimates may be too low. The uncertainties are, however, large. Further work on urban area characteristics, such as built-up area, is therefore required to reduce uncertainties.

Figure A1. Frequency distribution of selected cities; on the horizontal axis, the number of inhabitants is given in 1 000s; note that for the first five classes the upper value of the population range is indicated



A1.3. Collection of AQ monitoring data

Measurement data have been collected from as many of the selected cities as possible for SO_2, NO_2, and particulate matter (PM_{10}) and Pb, covering the years 1992–96. For NO_2, the measurement database contains 953 site-years of data for the annual average and 592 site-years of data for 1 hour maximum concentrations. For calculating averages, only cities with more than one site-year of data have been selected. Measurement sites classified as directly influenced by traffic (kerb site, road site) were excluded. The information on station classification is, however, not always available and not always reliable, which may result in bias in the concentrations relative to the urban background concentrations.

In the case of particulate matter (PM_{10}), 204 site-years were collected for annual average concentrations and 148 site-years for reported maximum 24-h concentrations. In order to give a clearer picture of the composition of emission sources in the selected cities, a database of SO_2 measurements, covering the period 1990–94, has also been used. The urban population covered by the database is summarised in Table A2.

Table A2. Urban population covered by the measurement database

	NO_2	PM_{10}	SO_2
Data for annual average concentrations	88.9 million	51.7 million	72.6 million
Data for maxima (1 h for NO_2 and SO_2, 24 h for PM_{10})	68.4 million	45.6 million	36.6 million

The sources of the data are mainly the Airbase database (EEA, 1999), the EEA/ETC-AQ database for air quality in Europe 1993 report (Larssen and Hagen, 1996), and national data (Austria, Belgium, France, Germany, UK). For PM_{10}, the database also consists of data collected by the Regional Policies and Cohesion DG Working Group on Particulate Matter. References to these data sources are summarised in Table A3. Benzene and B(a)P are not yet included in Airbase; monitoring data have been obtained from the benzene position paper and from various national data sources.

Table A3. Sources of city air-quality data

Sources of urban air quality data for NO_2, PM_{10} and SO_2:
1. Airbase (EEA ETC/AQ).
2. UK monitoring data, downloaded in January 1999 from the Department of the Environment, Transport and the Regions (http://www.aeat.co.uk/netcen/airqual).
3. Umweltbehörde Abteilung Luft, Hamburg, Germany, Hr. Hache, pers. comm. 24.10.95.
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Since data were generally scarce, empirical conversion factors were used to interconvert statistics; for instance, if 98 percentile values were needed and annual averages were available for certain stations only, the annual averages were converted by taking the average ratio between 98 percentile and annual average for stations where both statistics were available. This procedure was adopted for the cQ model.

A2. Urban emissions

A2.1. Top-down approach

Urban emissions were estimated using a top-down approach, proposed by the Topic Centre on Air Emissions (EEA, 1996b). While this simple procedure is clearly approximate, it offers the advantage of providing consistent emission estimates for all selected cities in Europe. Estimates were made on the basis of available data:

- national emissions per sector as given in the Auto-Oil base case scenario (SENCO, 1999);
- detailed information on emissions from Corinair 90 at a NUTS 3 geographical level and a SNAP1 level of sector detail, available for SO_2, NO_x, CO and VOC (EEA, 1996a).

Corinair defines source categories of air emissions in the *Selected nomenclature for sources of air pollution* (SNAP). The 375 detailed SNAP3 level sources can be aggregated into 77 source sub-sectors (SNAP2) and further into 11 main sectors (SNAP1) as given in Table A4.

The top-down approach is different for large point sources and for low-level area sources. Large point sources with known coordinates were allocated to a city when their distance to the city centre is less than the radius of the city. The radius was estimated from the urban surface area (see section A1) approximating the city area to a circle.

For the area sources, the top-down approach involved scaling of NUTS 3 emission estimates to a local level through the use of indicators of the proportion of a particular activity occurring in the specified local area. For each city, the urban emission was estimated following this pro rata approach according to:

$$E_{city,group,90,X} = E_{NUTS3,group,90,X} \times \frac{S_{city,group}}{S_{NUTS3,group}} \quad (1)$$

where:

X is one of the pollutants SO_2, NO_x, CO or VOC,
$E_{city,group,90,X}$ is the urban emission of pollutant X related to a specific economic sector (i.e. specific SNAP-code) for the reference year 1990,
$E_{NUTS\ 3,group,90,X}$ is the NUTS 3 emission of pollutant X for this sector and
$S_{city,group}$ and $S_{NUTS\ 3,group}$ are statistical indicators related to this sector at the urban and NUTS 3 level, respectively.

Table A4. Definition of SNAP1 sectors (EEA, 1997)

code	Name
1	Combustion in energy and transformation industries
2	Non-industrial combustion plants
3	Combustion in manufacturing industry
4	Production processes
5	Extraction and distribution of fossil fuels/geothermal energy
6	Solvent and other product use
7	Road transport
8	Other mobile sources and machinery
9	Waste treatment and disposal
10 ([1])	Agriculture and forestry, land use and woodstock change
11 ([1])	Nature

(a) In estimating urban emissions, all emissions from SNAP Sectors 10 and 11 are excluded.

In the current application, the population was used as a proxy for the statistical indicator for all sectors. Emissions from agriculture and nature were assumed to occur in rural areas and were excluded from the urban emissions.

For some pollutants (benzene, B(a)P, Pb and PM_{10}), disaggregated emissions on a NUTS 3 level were not available. For these components only national totals (reference year 1990) disaggregated at a SNAP1 level were available (Berdowski et al., 1997a; Berdowski et al., 1997b; Visschedijk et al., 1999; SENCO, 1999). To estimate urban emissions for these pollutants it might be assumed that the geographical distribution at NUTS 3 level follows the distribution of one of the other pollutants. Urban emissions were then calculated by appropriate scaling:

$$E_{city,group,90,Z} = \left\{ E_{NUTS3,group,90,X} \times \frac{E_{country,group,90,Z}}{E_{country,group,90,X}} \right\} \times \frac{S_{city,group}}{S_{NUTS3,group}} \quad (2)$$

where

Z is benzene, B(a)P, Pb or PM_{10},
$E_{country,group,90,X}$ is the national total emission of pollutant X (SO_2, NO_x, CO or VOC) for the sector *group*.

However, the sector split at EU-15 level for each of the pollutants benzene, B(a)P, Pb and PM_{10} is quite different from the sector splits of the classical compounds SO_2, NO_x, CO and VOC (SENCO, 1999; Berdowski et al., 1997a; Visschedijk et al., 1999). Since it is not expected that the differences in pollutant sector splits will be more alike at national level, urban emissions for these compounds were estimated

following an approach developed by Visschedijk et al. (1999) in preparing emissions of heavy metals and persistent organic pollutants in the framework of the EEA report 'Environment in the European Union at the turn of the century' and the Environment DG commissioned study 'Economic assessment of priorities for a European environmental policy plan'. As indicated above, point sources were attributed to a city depending on their location and the location and size of the city. A proxy, indicating the ratio between the population of the city and the total population of the country was used to apportion area sources to cities. To account for the differences in traffic characteristics between urban and rural area, country specific, pollutant specific correction factors were introduced.

Scaling of emissions to other years

Emissions for years other than 1990 were not available for any of the pollutants at a NUTS 3 level of detail. Urban emissions for 1995 were estimated by scaling the 1990 emission data according to the ratio of national emissions (at a SNAP1 level) in 1990 and 1995, see Equation (3):

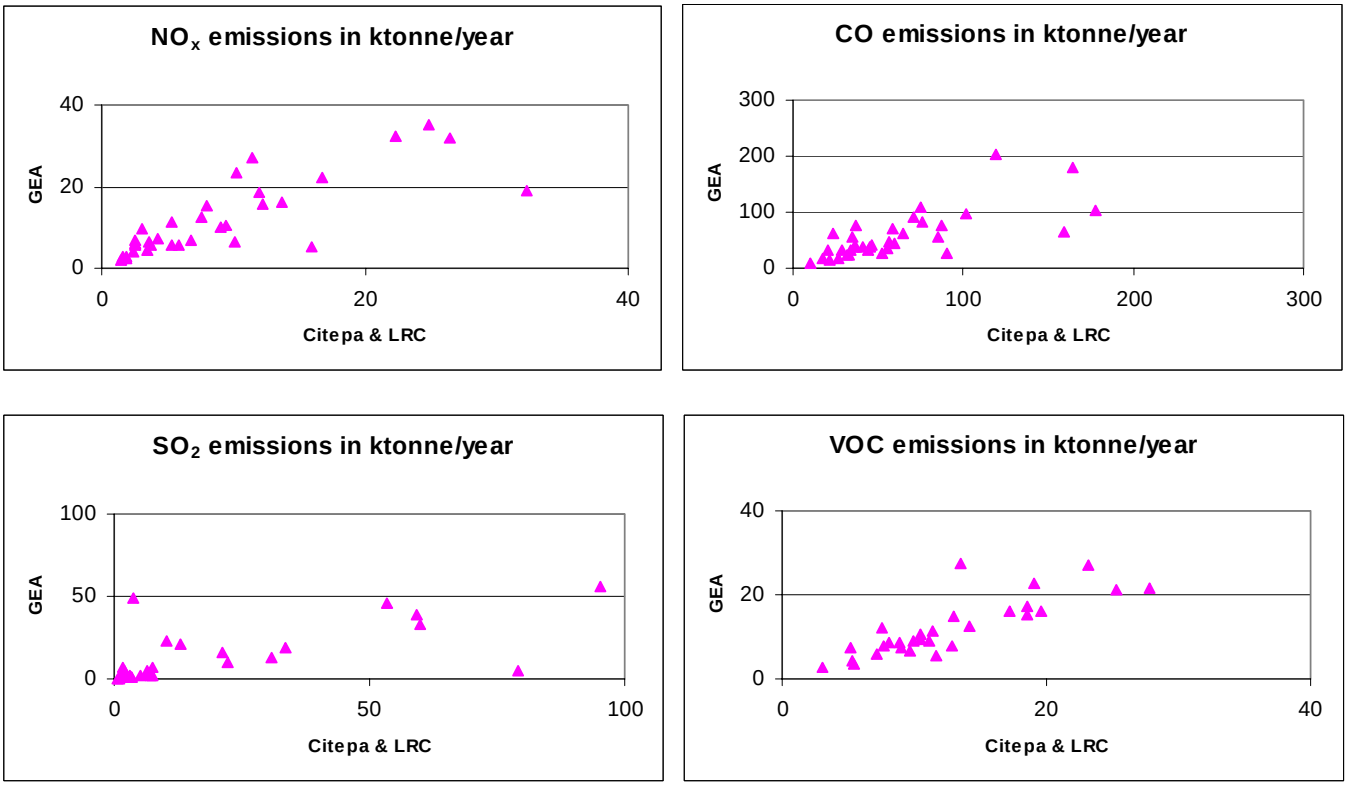
$$E_{city,group,95,X} = E_{city,group,90,X} \times \frac{E_{country,group,95,X}}{E_{country,group,90,X}} \qquad (3)$$

Information on 1995 was obtained from the AOP II base case Version 5 (SENCO, 1999) for NO_x, SO_2, CO, VOC, benzene and PM_{10}; and for B(a)P and Pb from Visschedijk et al. (1999). Additional information on 1994 emissions was obtained from EEA (1997).

The urban emissions as calculated by these procedures are presented in Annex 3.

For the ozone calculations, further processing of urban emissions was necessary. A default VOC split for each of the 11 Corinair source sectors was supplied by DNMI (Sector 7 (road traffic emissions) is a mixture of gasoline and diesel). The diurnal variations of emissions for various source categories were taken from the AOP I study for the seven countries considered (i.e. France, Germany, Greece, Ireland, the Netherlands, Spain and the United Kingdom). Urban emissions in Austria, Denmark, Finland and Sweden were assumed to have the same diurnal variation as Germany, Luxembourg as in France, Belgium as in the Netherlands, Portugal as in Spain and Ireland as in the United Kingdom.

Figure A2. Comparison between urban emission estimates in a number of cities in France and the UK and this study (GEA)



A2.2. Sensitivity analysis and validation

The allocation of point sources critically depends on the assumed size of the urban area. This effect was investigated in two sensitivity runs for urban NO_x emissions recalculated (1) with an urban radius increased by 5 km; and (2) with a uniform increase in radius of 10 %. The results indicate that for small cities, the 5 km increase may have a large effect since it may easily lead to a doubling of the urban area. However, for the vast majority of cities, the sensitivity calculation results in emission differences not exceeding 10 %.For major French cities, urban emissions were also calculated by Citepa (Fontelle et al., 1997). In the UK, the London Research Centre has collected emission data for eight cities. A comparison (see Figure A2) shows a reasonable agreement between the GEA and the independent French and British estimates. The largest differences are found in the SO_2 emission estimates, most probably caused by different treatment of large point sources. For NO_x, GEA estimates are higher than the Citepa results.

A3. Air pollution models

In the GEA study, three air pollution models were used for the calculation of air-quality parameters from urban emissions:

- The cQ model for 'inert' species where sufficient monitoring data were available.
- The UAQAM for 'inert' species in all cities.
- The OFIS model, which was applied to calculate ozone concentrations for a limited number of cities.

It is recognised that the methodology of the selected models may not be appropriate for locations with extreme orographic influence resulting in inhomogeneous flow patterns; such conditions cannot be resolved by the OFIS model and UAQAM .

A3.1. cQ model

The cQ model is an empirical model which relates urban emissions to observed concentrations. This model has been applied for 'inert' species and for cities with sufficient air-quality monitoring data available. The requirements on available monitoring data limit the use of the cQ model to SO_2, NO_2 and PM_{10}. The model uses the empirical ratio between urban emissions Q and the air concentration c, corrected for regional contributions, to estimate air concentrations from available emission data. Different types of sources are assumed to contribute differently to the calculated concentrations by using effectivity factors.

The cQ model was previously used in a study for the Regional Policies and Cohesion DG (CEC, 1998). For many of the cities, the cQ relationships for SO_2, NO_x/NO_2 and (for some cities) also PM_{10}, gave consistent results for all compounds. This suggests some credibility of the method; however, its weak points should be recognised. Uncertainties include:

- Uncertainties in reference emission estimates. Results are affected by the accuracy of relative sector source strengths and relative reductions, rather than absolute emission figures.
- Uncertainty related to the effectivity factor for traffic emissions versus other emission categories. This plays a minor role in the current study, where only traffic related measures are considered.
- Representativeness of monitoring stations. Data for PM_{10} is considerably less complete than for NO_2 or SO_2. Any EU-wide PM_{10} analysis will be limited by this lack of data.
- Representativeness of meteorological conditions.

A strength of the cQ model is its basis in measured air quality.

A3.2. UAQAM

The urban air-quality assessment model (UAQAM) is a dispersion model calculating (annual) average city background concentrations and exceedances of air-quality thresholds on an hourly or daily basis from actual meteorology and urban emissions.

Input data are limited to urban emissions, city area, regional background concentrations and meteorological observations only. The structure of the model is transparent; simple parameterisations simulate the most important phenomena. A full description of the model has been given by van Pul et al. (1996).

UAQAM contains three modules in which emissions, meteorological parameters and dispersion are modelled. In a fourth module, the hourly and seasonal variations in the regional background concentration of the cities are parameterised. The UAQAM does not include atmospheric chemistry. The model has been applied in the GEA study for all inert species for the full list of cities.

From NO_x concentration, NO_2 concentration is estimated using an empirical relation (BUWAL, 1997):

$$NO_2 = 0.055 * NO_x + 55 * \left(1 - e^{-NO_x * 0.01173}\right)$$

This relation is based on monitoring data in Germany, Austria and Switzerland. Compared to the well-known NO_2/NO_x relation used in Auto-Oil I, this relation is nearly equivalent at lower NO_x concentrations. At high NO_x-levels the BUWAL-equation estimates lower NO_2 concentrations, which are in better agreement with measurements.

Statistical information on activity patterns (traffic intensity, industrial activity, relation between heating demand and ambient temperature) is used to obtain seasonal and diurnal variations in emissions.

A3.3. OFIS model

The OFIS (ozone fine structure) model is a photochemical dispersion model for calculating ground level ozone concentrations in and around urban areas.

In contrast to earlier approaches, the OFIS model allows an adequate description of urban photochemistry and atmospheric dynamics with a very low computational effort (Sahm and Moussiopoulos, 1999). This extends its applicability to longer time periods. This Eulerian photochemical dispersion model is capable of simulating transport and photochemical transformation processes in an urban plume. Thus, it may be used for calculating urban scale ozone concentrations (e.g. for exposure analyses or for assessments of control strategies) based on large-scale meteorological information and long-range transport information over a longer time period.

Having been derived from well-tested full 3D models, the OFIS model retains all elements necessary for a realistic assessment of urban scale ozone levels. The conceptual basis of OFIS is a coupled 1D/2D approach. Background boundary layer concentrations are computed with the multi-layer box model embedded in OFIS for a domain of 150×150 km^2 with the city in the centre and rural area all around. For each day in the period considered, pollutant transport and transformation downwind of each city is calculated in 5 km steps (assuming the wind direction is valid for that day), an initial plume width according to the city diameter and a plume widening angle of 30°. Large emitters in the vicinity of the urban area are taken into account in the urban plume module depending on the wind direction prevailing on the day. Local circulation systems (such as the sea breeze in coastal areas) are taken into account by inversing the wind direction of the urban plume in the lower two layers (i.e. up to the height of the mixed layer) in the afternoon hours of days with weak synoptic forcing and off-shore wind direction. Dry deposition is accounted for by using a three-resistance model approach. Biogenic emissions are taken into account for rural areas.

OFIS was applied in the Stuttgart area in the context of the European Commission's communication on an ozone strategy (Moussiopoulos et al., 1999). Regional background concentrations were derived from results of the EMEP model (Simpson et al., 1997). The EMEP/OFIS model cascade satisfactorily describes the levels of ozone exposure, resolving both downtown ozone titration and ozone formation in the urban plume of Stuttgart.

A4. Background concentrations

The contribution to urban air quality from the regional background depends on the pollutant. For NO_2, the urban concentrations are considerably higher than the concentrations outside urban areas. For particles, however, the differences are

smaller, and estimating their regional background concentrations is more critical. In modelling urban ozone levels, the regional background concentrations form an important factor.

In the models, a gradient from background (outside city) concentrations to city background concentrations to city hot spot concentrations was assumed. This background concentration outside the city was generally calculated by or derived from the EMEP MSC-W model for acidifying compounds (Jakobsen et al., 1997), the EMEP-MSC-W photochemical model (Simpson, 1993) or the long-range transport model TREND (van Jaarsveld, 1995, Eerens et al., 1998). Regional scale model results are not available for CO; in this case, background concentrations were estimated from monitoring data.

Regional background concentrations for ozone were taken from the EMEP-MSC-W photochemical model (Simpson, 1993). Regional background concentrations with the EMEP model were calculated for base case for 1995 and 2010 (using 1995 meteorology).

Background concentrations for primary PM_{10} were calculated with the TREND model (Eerens et al., 1998) using the available emission inventory (Berdowski et al., 1997b) for 1993 and meteorological data for 1990. The concentrations for the centres of the EMEP grid cells were used as estimates of regional primary PM_{10} concentrations.

The secondary inorganic particles that form a substantial part of the PM_{10} concentrations were modelled as a sum of ammonium nitrate and ammonium sulphate, based on the EMEP model results, for 150 x 150 km grid cells. They were calculated by the 1996 version of EMEP model considering all the European sources, for 1995 and 2010 using the base case emissions (Jakobsen et al., 1997; Tsyro, 1998). Data about secondary organic particles is limited, and they have not been included in the model for this study.

For NO_x and SO_2, daily average regional background concentrations were taken from EMEP model calculations. A normalised diurnal variation calculated from data for seven monitoring years at five background stations in the UK was used to estimate hourly concentrations from these daily EMEP background values.

Background concentrations for CO were not available from long-range transport models. Based on measurements at rural stations in the United Kingdom and the Netherlands an annual average level of 0.45 mg/m3 was estimated for 1995. The temporal variation in background levels is described as a log-normal distribution with a 50-percentile value of 0.45 mg/m3 and a sigma value of 0.6. Temporal variations in background concentrations were assumed to correlate perfectly with the variations in urban levels, that is, the 98-percentile values of the urban and regional contributions are reached at the same moment.

Regional background concentrations for 2010 were simulated by a log-normal distribution with a P50-value of 0.35 mg/m^3. EU-15 emissions decrease between 1990 and 2010 by more than 50 %. Since there are contributions to the concentration from emissions from other European countries and there is an *in situ* contribution to CO from photochemical oxidation, it is assumed that the decrease in regional background concentrations will be less than the decrease in European emissions.

For benzene, Pb and B(a)P, the regional background concentrations were derived from TREND calculations. For benzene, data from an existing TREND study were scaled with the ratio of EU-15 emission totals in TREND and in the Auto-Oil II base case.

Annex 2: List of selected cities

List of cities taken into account in the EEA/ETC approach, modelling of concentrations of ozone and 'inert' species

City	Country	Latitude	Longitude	Population	OFIS	AOP	Area (km^2)
Graz	A	47.08	15.37	237 810	o3		46.8
Innsbruck	A	47.28	11.42	118 112			19.3
Klagenfurt	A	46.63	14.34	89 502			23.6
Linz	A	48.32	14.31	203 044			52.9
Salzburg	A	47.80	13.06	143 973			29.8
Wien	A	48.21	16.18	1 539 848	o3		190.8
Antwerpen	B	51.20	4.39	668 125	o3		284.5
Bruxelles/Brussel	B	50.84	4.34	960 324	o3		441.2
Charleroi	B	50.42	4.45	294 962			182.5
Gent	B	51.05	3.71	250 666			123.9
Liege	B	50.64	5.56	484 518			241.4
Namur	B	50.47	4.86	103 935			56.9
Aschaffenburg	D	49.58	9.10	59 257			18.4
Augsburg	D	48.35	10.90	262 110			75.3
Berlin	D	52.51	13.42	3 472 009	o3	aop	587.0
Bielefeld	D	52.03	8.53	324 067			59.3
Bonn	D	50.73	7.10	293 072			52.1
Brandenburg	D	52.25	12.34	94 872			24.6
Braunschweig	D	52.27	10.54	254 130			47.4
Bremen	D	53.09	8.83	549 122	o3		105.2
Chemnitz	D	50.83	12.92	274 162			71.0
Cottbus	D	51.72	14.35	125 643			40.0
Darmstadt	D	49.87	8.65	139 063			28.3
Dortmund	D	51.52	7.45	600 918	o3		159.3
Dresden	D	51.05	13.75	474 443			184.8
Düsseldorf	D	51.22	6.76	572 638	o3		113.7
Emden	D	53.23	7.13	51 186			16.6
Erlangen	D	49.60	11.03	101 450			16.5
Essen + environ	D	51.45	7.01	1 848 732			364.3
Frankfurt-am-Main	D	50.12	8.68	652 412	o3		117.6
Freiburg	D	48.00	7.87	198 496			33.2
Halle	D	51.48	11.95	290 051			58.1
Hamburg	D	53.56	10.00	1 705 872	o3		379.1
Hanau	D	50.14	8.92	86 402			30.3
Hannover	D	52.37	9.72	525 763	o3		139.0
Heidelberg	D	49.42	8.70	138 964			22.3
Heilbronn	D	49.13	9.23	122 253			27.2
Ingoldstadt	D	48.77	11.44	110 910			25.3
Kaiserslautern	D	49.45	7.78	101 910			25.4
Karlsruhe	D	49.00	8.40	277 011			47.0
Kassel	D	51.30	9.50	201 789			63.3
Kiel	D	54.34	10.11	246 586			51.3
Koblenz	D	50.35	7.60	109 550			35.9
Köln	D	50.94	6.95	963 817	o3	aop	107.3
Leipzig	D	51.33	12.42	481 121			160.9
Lubeck	D	53.87	10.67	216 854			48.4
Magdenburg	D	52.13	11.62	265 379			69.4
Mainz	D	50.00	8.27	184 627			35.0
Mannheim/Ludwigshafen	D	49.50	8.47	484 106	o3		109.1
Monchengladbach	D	51.20	6.42	266 073			52.6

City	Country	Latitude	Longitude	Population	OFIS	AOP	Area (km^2)
München	D	48.13	11.59	1 244 676	o3		256.6
Münster (Westf.)	D	51.97	7.62	264 887			38.6
Nürnberg	D	49.45	11.09	495 845			118.4
Rostock	D	54.14	12.03	232 634			42.1
Saarbrücken	D	49.24	7.00	189 012			120.3
Schwerin	D	53.62	11.40	118 291			11.8
Stuttgart	D	48.77	9.18	588 482	o3		99.1
Trier	D	49.45	6.39	95 536			21.6
Ulm	D	48.40	10.00	115 123			26.7
Wetzlar	D	50.33	8.30	51 997			18.2
Wiesbaden	D	50.09	8.25	266 081			44.0
Wilhelmshaven	D	53.32	8.07	99 230			17.3
Wuppertal	D	51.25	7.17	383 776			120.7
Ålborg	DK	57.05	9.94	159 056			41.8
Århus	DK	56.17	10.22	277 477			71.9
Esbjerg	DK	55.48	8.47	70 220			19.8
København	DK	55.69	12.57	1 353 333	o3		247.9
Odense	DK	55.41	10.42	182 617			58.3
Alicante	E	38.35	– 0.48	267 421			20.9
Barcelona	E	41.41	2.16	2 625 547	o3		129.2
Bilbao	E	43.24	– 2.95	550 452	o3		37.4
Cordoba	E	37.88	– 4.77	305 894			28.4
Gijón	E	43.53	– 5.67	259 067			27.0
Granada	E	37.17	– 3.58	256 784			12.4
Madrid	E	40.41	– 3.73	2 976 064	o3	aop	194.4
Málaga	E	36.72	– 4.42	523 450			54.0
Murcia	E	37.98	– 1.13	331 898			17.0
Palma de Mallorca	E	39.58	2.65	298 971			24.1
Sevilla	E	37.39	– 6.00	678 902			59.0
Valencia	E	39.48	– 0.40	749 361			66.3
Valladolid	E	41.65	– 4.75	331 885			20.6
Vigo	E	42.22	– 8.73	276 109			62.4
Zaragoza	E	41.65	– 0.90	598 078			29.0
Espoo	FI	60.18	24.73	184 577			22.3
Helsinki	FI	60.21	25.00	1 016 291	o3	aop	242.0
Jyvoskylo	FI	62.28	25.86	67 026			8.3
Aix-en-Provence	F	43.51	5.45	123 778			14.1
Amiens	F	49.90	2.29	158 735			30.3
Arras	F	50.30	2.76	80 477			25.3
Besancon	F	47.23	6.03	124 174			28.6
Bordeaux	F	44.83	– 0.57	715 187			152.9
Caen	F	49.18	– 0.38	195 429			62.6
Calais	F	50.95	1.86	102 414			34.7
Clermont-Ferrand	F	45.78	3.08	249 461			56.6
Colmar	F	48.08	7.35	82 468			20.4
Creil	F	49.27	2.48	82 479			19.4
Dunkerque	F	51.04	2.38	195 705			84.6
Grenoble	F	45.18	5.71	419 696	o3		79.2
La-Rochelle	F	46.16	– 1.18	103 470			32.9
Le-Havre	F	49.52	0.14	255 818			38.2
Lens-Bethune	F	50.44	2.83	582 719			163.1
Lille	F	50.65	3.07	964 669	o3		201.1
Lyon	F	45.76	4.83	1 286 492	o3	aop	268.4
Marseille	F	43.29	5.36	1 258 102	o3		143.3
Montbeliard	F	47.52	6.80	118 996			46.6
Montpellier	F	43.60	3.88	263 426			32.3
Mulhouse	F	47.75	7.35	228 385			58.9

City	Country	Latitude	Longitude	Population	OFIS	AOP	Area (km^2)
Nancy	F	48.70	6.20	328 187			68.0
Nantes	F	47.23	– 1.60	510 419	o3		113.1
Nice	F	43.70	7.27	533 740			67.7
Paris-(urban-a	F	48.87	2.33	9 069 499	o3		996.6
Reims	F	49.27	4.03	208 354			40.5
Rennes	F	48.10	– 1.68	252 853			50.8
Rouen	F	49.44	1.08	383 446	o3		104.9
Saint-Etienne	F	45.43	4.38	314 393			56.3
Strasbourg	F	48.58	7.75	398 163	o3		95.3
Toulon	F	43.12	5.92	464 195			82.5
Toulouse	F	43.61	1.43	684 215	o3		150.6
Tours	F	47.38	0.70	288 204			66.6
Valenciennes	F	50.37	3.53	340 309			72.8
Athinai	EL	37.99	23.75	3 072 922	o3	aop	284.6
Thessaloniki	EL	40.62	22.97	749 048	o3		49.3
Dublin	IRL	53.34	– 6.27	915 516	o3	aop	195.6
Bari	I	41.12	16.87	341 273			60.3
Bologna	I	44.45	11.33	404 322	o3		73.6
Catania	I	37.53	15.12	330 037			108.3
Firenze	I	43.79	11.24	402 316	o3		61.9
Genova	I	44.39	8.97	675 659	o3		63.4
Livorno	I	43.49	10.37	167 445			28.1
Messina	I	38.22	15.55	272 461			27.2
Milano+	I	45.43	9.20	1 461 210	o3	aop	381.7
Modena	I	44.66	10.93	176 148			27.9
Napoli	I	40.83	14.25	1 054 601			160.6
Palermo	I	38.10	13.38	697 162			76.0
Piacenza	I	45.02	9.73	102 252			18.1
Ravenna	I	44.37	12.20	135 435			25.3
Reggio-nell-em	I	44.71	10.64	131 419	o3		24.3
Roma	I	41.85	12.46	2 693 383	o3		214.9
Sassari	I	40.72	8.57	116 989			7.9
Siracusa	I	37.02	15.22	126 136			14.6
Terni	I	42.62	12.64	107 333			21.6
Torino	I	45.08	7.67	961 916	o3		125.0
Trento	I	46.04	11.11	101 112			21.1
Venezia	I	45.47	12.34	308 717			37.3
Verona	I	45.43	11.00	252 689			37.3
Luxembourg	L	49.62	6.13	76 446	o3		45.1
Amsterdam	NL	52.36	4.90	1 100 764	o3		123.9
Apeldoorn	NL	52.22	5.95	149 659			31.0
Dordrecht	NL	51.80	4.66	213 519			27.9
Eindhoven	NL	51.44	5.50	394 469			47.4
Haarlem	NL	52.39	4.63	213 392			26.6
Heerlen/Kerkrade	NL	50.90	5.98	270 535			38.0
Nijmegen	NL	51.84	5.86	147 346			31.6
Rotterdam/Vlaardingen	NL	51.92	4.48	1 155 542	o3		165.9
s-Gravenhage	NL	52.09	4.26	694 733			67.6
Utrecht	NL	52.11	5.11	546 433	o3	aop	59.6
Zaanstad	NL	52.46	4.81	147 363			18.7
Lisbao	P	38.72	– 9.15	1 658 000	o3		138.3
Porto	P	41.14	– 8.64	1 174 461	o3		80.7
Setubal	P	38.50	– 8.92	103 634			7.5
Goteborg	S	57.71	11.95	444 553	o3		175.0
Jonkoping	S	57.80	14.21	114 811			39.6
Karlstad	S	59.41	13.51	53 125			31.1
Linkoping	S	58.43	15.64	130 489			34.6

City	Country	Latitude	Longitude	Population	OFIS	AOP	Area (km^2)
Lund	S	55.71	13.19	64 628			21.0
Norrkoping	S	58.60	16.18	123 240			33.8
Orebro	S	59.18	15.05	118 606			51.4
Stockholm	S	59.27	18.09	880 096	o3		319.4
Uppsala	S	59.86	17.66	181 191			45.2
Belfast	UK	54.59	– 5.94	297 100			131.6
Bristol	UK	51.44	– 2.60	399 243	o3		97.8
Cardiff	UK	51.47	– 3.20	300 038			64.2
Coventry	UK	52.42	– 1.50	302 514			89.9
Doncaster	UK	53.53	– 1.12	292 501			38.1
Edinburgh	UK	55.96	– 3.22	443 600			85.8
Glasgow	UK	55.87	– 4.26	680 000	o3		414.1
Greater-Manche	UK	53.51	– 2.27	2 319 558	o3		397.3
Kingston-upon-Hull	UK	53.76	– 0.35	269 144			74.4
Leicester	UK	52.67	– 1.18	293 387			84.2
Liverpool	UK	53.42	– 3.02	1 409 493	o3		195.2
London	UK	51.50	– 0.10	10 569 997	o3	aop	1 191.3
Nottingham	UK	52.97	– 1.17	282 440			153.4
Plymouth	UK	50.38	– 4.17	255 815			61.4
Sheffield/Rotherham	UK	53.39	– 1.48	786 381	o3		153.6
Southampton/eas	UK	50.90	– 1.39	211 718			49.5
Stevenage	UK	51.90	– 0.20	74 757			17.4
Stoke on Trent	UK	53.00	– 2.18	377 334			86.7
Sunderland	UK	54.93	– 1.43	297 226			254.1
Teesside	UK	54.62	– 1.23	381 456			137.5
Tyneside	UK	54.99	– 1.60	776 304	o3		254.1
West-Midlands	UK	52.51	– 1.93	2 080 232	o3		520.3
West-Yorkshire	UK	53.81	– 1.58	1 523 496	o3		321.4

Annex 3: Urban emissions in selected cities

Urban emissions of SO_2, NO_x, CO, Pb, benzene and PM_{10} have been estimated using the methods outlined in Chapter 4. For all pollutants, the starting point of the emission estimates are the national emission totals given in the AOP-base case Version 4 of April 1999. To illustrate the uncertainties in PM_{10} emissions, the urban emissions calculated for AOP-base case Version 5 (May 1999) are included as well. All emissions are given in tonne/year; NO_x emissions are expressed as tonne NO_2 per year.

	SO_2	SO_2	NO_x	NO_x	CO	CO	Pb	Pb	Benzene	Benzene	PM_{10}-V4	PM_{10}-V4	PM_{10}-V5	$PM1_0$-V5
City	Tonne/ year 1995	Tonne/ year 2010	Tonne NO_2/yr 1995	Tonne NO_2yr 2010	Tonne/ year 1995	Tonne/ year 2010	Tonne/ year 1995	Tonne/ year 2010	Tonne/ year 1995	Tonne/ year 2010	Tonne/ year 1995	Tonne/ year 2010	Tonne/ year 1995	Tonne/ year 2010
Graz	2 649	1 796	5 487	2 991	73 864	63 920	5.32	2.92	136.7	83.3	768	747	671	645
Innsbruck	768	443	2 389	1 291	17 343	12 425	2.42	1.20	67.9	41.4	298	280	250	229
Klagenfurt	1 146	634	2 135	1 197	16 968	13 425	1.84	0.91	51.4	31.3	226	212	190	173
Linz	2 168	1 521	5 983	3 222	57 121	48 091	9.10	8.41	116.7	71.1	5 731	6 657	5 631	6 607
Salzburg	930	512	3 228	1 796	22 114	16 220	2.95	1.46	82.7	50.4	364	341	305	279
Wien	4 732	3 015	25 844	12 313	110 088	45 662	31.86	15.92	885.0	539.1	3 897	3 653	3 273	2 990
Antwerpen	34 418	32 229	30 838	23 168	50 928	26 250	76.49	68.09	299.3	175.0	4 673	5 204	4 602	5 055
Bruxelles/Brus	17 139	8 670	16 752	10 453	51 561	30 755	34.64	22.57	430.2	251.5	4 031	4 004	3 947	3 882
Charleroi	15 329	7 663	10 768	6 947	23 019	18 598	40.84	40.77	132.1	77.3	6 646	7 164	6 574	7 087
Gent	26 054	14 998	13 900	7 900	14 318	6 461	49.28	48.44	112.3	65.7	8 078	8 950	8 006	8 868
Liege	17 547	13 759	91 341	75 499	96 097	81 957	56.99	55.04	217.1	126.9	8 133	8 801	8 047	8 701
Namur	1 131	441	2 265	1 181	5 988	2 133	2.65	1.25	46.6	27.2	286	264	278	251
Aschaffenburg	146	95	1 149	508	5 730	2 826	0.82	0.57	21.5	8.0	283	149	267	133
Augsburg	605	446	3 202	1 772	18 698	10 611	3.66	2.53	95.1	35.4	1 258	663	1 186	591
Berlin	21 951	13 669	66 153	31 408	274 739	184 455	126.13	105.23	1 260.2	469.0	47 276	30 262	46 371	29 205
Bielefeld	885	593	6 095	2 789	29 305	14 711	4.71	3.27	117.6	43.8	1 574	835	1 485	746
Bonn	668	450	5 039	2 324	28 492	13 814	4.05	2.80	106.4	39.6	1 434	764	1 354	684
Brandenburg	1 328	623	808	486	10 955	8 338	1.31	0.91	34.4	12.8	454	239	428	213
Braunschweig	602	401	4 546	2 198	23 473	11 670	18.91	16.71	92.2	34.3	1 230	651	1 161	582
Bremen	1 637	1 104	25 297	11 554	46 147	23 565	15.50	12.30	199.3	74.2	4 068	2 402	3 920	2 248
Chemnitz	3 276	1 632	1 916	1 212	26 491	20 515	3.90	2.70	99.5	37.0	2 806	1 900	2 745	1 838
Cottbus	2 774	1 557	2 284	1 181	15 917	13 328	1.74	1.20	45.6	17.0	601	316	566	282
Darmstadt	320	222	2 301	1 124	11 665	5 639	1.93	1.34	50.5	18.8	669	353	631	315
Dortmund	1 774	1 310	15 480	8 473	53 538	27 627	29.74	25.53	218.1	81.2	8 079	5 059	7 913	4 864
Dresden	8 358	4 759	6 268	3 416	50 339	40 335	15.49	12.78	172.2	64.1	7 786	5 388	7 688	5 274
Düsseldorf	1 832	1 232	16 068	8 260	52 716	30 063	9.74	6.87	207.8	77.3	4 581	2 933	4 442	2 792
Emden	137	95	573	334	3 444	2 000	0.71	0.49	18.6	6.9	245	129	231	115
Erlangen	330	215	5 953	2 550	11 645	5 673	1.42	0.98	36.8	13.7	495	263	468	236
Essen+ environ	10 225	8 382	53 132	27 500	162 375	84 380	48.15	37.98	671.0	249.7	17 820	10 108	17 387	9 584
Frankfurt -M	3 032	2 470	18 801	9 616	66 567	29 971	9.22	6.38	236.8	88.1	3 199	1 706	3 021	1 528
Freiburg	429	302	2 277	1 237	13 982	7 709	2.75	1.90	72.0	26.8	953	502	898	448
Halle	6 873	3 971	3 569	1 968	33 817	27 711	4.01	2.77	105.3	39.2	1 387	729	1 307	650
Hamburg	6 741	5 617	25 859	12 897	124 468	63 348	25.86	18.02	619.2	230.4	8 902	4 895	8 441	4 434
Hanau	283	186	1 903	880	8 610	3 998	2.32	1.69	31.4	11.7	737	480	716	459
Hannover	1 270	866	8 479	4 203	43 205	22 491	7.94	5.53	190.8	71.0	2 668	1 448	2 526	1 305
Heidelberg	302	214	1 498	815	9 543	5 310	1.92	1.33	50.4	18.8	664	349	626	311
Heilbronn	611	442	7 549	3 453	9 681	5 616	1.69	1.17	44.4	16.5	584	307	551	274
Ingoldstadt	293	199	2 127	991	10 519	5 276	2.66	1.93	40.3	15.0	624	355	595	325
Kaiserslautern	254	182	1 352	717	7 573	4 059	1.42	0.98	37.0	13.8	490	259	462	231
Karlsruhe	1 546	1 388	10 582	5 424	32 712	15 745	3.94	2.73	100.5	37.4	1 356	722	1 280	646

City	SO_2 Tonne/ year 1995	SO_2 Tonne/ year 2010	NO_x Tonne NO_2/yr 1995	NO_x Tonne NO_2yr 2010	CO Tonne/ year 1995	CO Tonne/ year 2010	Pb Tonne/ year 1995	Pb Tonne/ year 2010	Benzene Tonne/ year 1995	Benzene Tonne/ year 2010	PM_{10}-V4 Tonne/ year 1995	PM_{10}-V4 Tonne/ year 2010	PM_{10}-V5 Tonne/ year 1995	$PM1_0$-V5 Tonne/ year 2010
Kassel	413	296	1 973	1 140	12 436	6 806	3.32	2.34	73.2	27.3	1 048	575	993	520
Kiel	767	533	4 964	2 539	15 723	8 969	3.79	2.65	89.5	33.3	1 382	785	1 316	719
Koblenz	235	168	1 051	615	6 778	3 931	1.51	1.05	39.8	14.8	524	276	494	245
Köln	3 276	2 285	32 704	16 036	101 427	48 897	14.37	10.00	349.8	130.2	4 668	2 472	4 404	2 209
Leipzig	14 024	9 022	16 400	8 249	61 920	52 336	6.72	4.64	174.6	65.0	3 277	2 001	3 154	1 878
Lubeck	997	683	8 031	3 720	18 298	9 419	3.00	2.07	78.7	29.3	1 037	545	977	486
Magdenburg	5 086	2 787	3 381	1 857	30 972	25 383	3.67	2.53	96.3	35.8	1 269	667	1 196	595
Mainz	612	430	6 496	2 981	15 521	8 127	4.23	3.05	67.0	24.9	1 171	698	1 123	650
Mannheim/Ludwigshafen	5 882	5 250	31 120	16 808	44 075	23 126	9.28	6.61	175.7	65.4	3 532	2 216	3 411	2 094
Monchengladb	609	403	4 459	2 049	24 096	12 024	14.96	12.56	96.6	35.9	5 433	2 909	5 422	2 839
München	2 552	1 763	16 306	8 192	93 493	51 219	18.37	12.77	451.8	168.1	5 991	3 164	5 650	2 824
Münster(Westf)	925	614	6 882	2 990	26 465	12 858	3.68	2.54	96.1	35.8	1 276	674	1 203	602
Nürnberg	1 052	729	6 114	3 131	37 394	20 467	9.94	7.10	180.0	67.0	3 049	1 797	2 920	1 666
Rostock	3 004	1 444	1 617	1 035	23 196	18 245	3.21	2.22	84.4	31.4	1 112	585	1 048	521
Saarbrücken	940	673	13 938	7 953	22 708	13 622	3.72	2.80	68.6	25.5	1 489	879	1 437	823
Schwerin	1 760	916	1 041	637	12 630	9 971	1.64	1.13	42.9	16.0	566	297	533	265
Stuttgart	1 255	876	8 027	4 017	45 410	23 890	8.69	6.04	213.6	79.5	2 847	1 508	2 686	1 347
Trier	223	154	1 309	666	7 444	3 887	1.32	0.91	34.7	12.9	457	240	431	214
Ulm	409	261	3 496	1 486	13 928	6 466	1.62	1.12	41.8	15.5	561	298	530	267
Wetzlar	193	121	1 656	693	6 363	2 762	0.72	0.50	18.9	7.0	249	131	234	117
Wiesbaden	607	430	4 158	2 064	22 138	10 718	3.68	2.54	96.6	35.9	1 272	669	1 199	596
Wilhelmshaven	228	158	1 130	634	6 826	3 871	1.37	0.95	36.0	13.4	474	250	447	222
Wuppertal	937	670	6 977	3 431	33 812	17 253	5.63	3.91	139.3	51.8	1 887	1 013	1 782	909
Ålborg	12 475	4 808	8 335	4 506	19 574	13 014	3.93	1.86	78.4	42.4	641	586	560	496
Århus	3 781	1 538	7 380	3 763	30 279	18 707	7.01	3.39	136.8	73.9	1 301	1 187	1 160	1 029
Esbjerg	16 118	6 026	6 114	3 079	8 648	5 384	1.77	0.85	34.6	18.7	321	293	285	253
København	21 908	8 310	32 213	15 194	195 936	149 362	33.30	15.72	667.3	360.6	5 262	4 803	4 572	4 042
Odense	15 946	5 990	9 428	4 687	19 917	11 137	4.76	2.36	90.0	48.7	1 002	915	910	809
Alicante	992	454	5 375	2 770	22 202	12 772	6.71	0.93	118.7	57.3	527	592	379	351
Barcelona	17 561	7 448	55 554	29 354	246 410	137 186	75.46	20.95	1 165.7	562.4	6 102	6 853	4 662	4 506
Bilbao	3 938	1 877	14 823	10 197	55 671	35 683	13.83	1.93	244.4	117.9	1 087	1 219	783	723
Cordoba	782	440	5 420	3 152	35 760	27 891	7.68	1.06	135.8	65.5	603	677	434	401
Gijón	3 299	1 857	5 676	3 640	38 424	30 698	38.00	42.62	115.0	55.5	4 569	4 002	4 442	3 809
Granada	539	291	3 951	2 088	16 783	10 276	6.44	0.89	114.0	55.0	506	568	364	337
Madrid	13 490	5 202	56 289	25 925	269 426	135 299	85.41	23.50	1 321.3	637.5	6 345	7 013	4 705	4 337
Málaga	1 002	522	11 950	7 178	42 211	22 054	13.15	1.83	232.4	112.1	1 071	1 213	783	742
Murcia	2 326	1 219	7 443	4 289	26 244	14 892	15.54	11.65	147.4	71.1	1 500	1 140	1 322	845
Palma de Mallorca	3 035	1 393	10 902	6 986	39 072	26 770	7.50	1.04	132.7	64.0	589	662	424	392
Sevilla	2 075	1 039	16 820	11 395	64 141	42 268	17.04	2.35	301.4	145.4	1 338	1 502	963	891
Valencia	3 101	1 503	14 534	7 865	49 486	25 467	20.58	5.18	332.7	160.5	1 685	1 758	1 273	1 084
Valladolid	1 607	827	6 540	3 762	34 216	22 915	8.37	1.21	147.4	71.1	659	737	475	438
Vigo	1 983	1 252	8 320	5 882	19 951	12 844	6.93	0.96	122.6	59.1	544	611	392	362
Zaragoza	5 757	4 151	12 547	7 317	51 734	30 431	18.94	6.99	265.5	128.1	1 384	1 487	1 055	950
Espoo	2 363	1 973	7 498	4 304	17 833	7 636	4.74	1.70	183.7	74.3	1 026	934	979	857
Helsinki	11 246	9 426	40 416	22 999	98 079	41 868	25.58	8.71	1 011.5	409.0	3 762	3 160	3 530	2 777
Jyvoskylo	836	854	2 282	1 223	6 612	2 858	1.69	0.58	66.7	27.0	248	208	233	183
Aix-en-Provence	376	203	3 127	1 275	20 074	7 773	6.11	1.54	87.8	40.9	305	261	273	222
Amiens	933	623	4 237	2 262	22 372	12 312	7.84	1.97	112.6	52.4	391	335	351	285
Arras	436	242	1 602	824	7 242	4 195	3.97	1.00	57.1	26.6	198	170	178	144
Besancon	425	199	2 621	1 107	17 934	9 039	6.13	1.54	88.1	41.0	306	262	274	223
Bordeaux	1 519	754	15 801	6 832	97 509	49 602	35.32	8.89	507.3	236.0	1 761	1 509	1 580	1 282
Caen	719	371	4 257	2 013	25 111	13 987	9.65	2.43	138.6	64.5	481	412	432	350
Calais	5 030	4 692	2 190	1 197	9 220	5 342	5.06	1.27	72.6	33.8	252	216	226	184

City	SO_2 Tonne/ year 1995	SO_2 Tonne/ year 2010	NO_x Tonne NO_2/yr 1995	NO_x Tonne NO_2yr 2010	CO Tonne/ year 1995	CO Tonne/ year 2010	Pb Tonne/ year 1995	Pb Tonne/ year 2010	Benzene Tonne/ year 1995	Benzene Tonne/ year 2010	PM_{10}-V4 Tonne/ year 1995	PM_{10}-V4 Tonne/ year 2010	PM_{10}-V5 Tonne/ year 1995	$PM1_0$-V5 Tonne/ year 2010
Clermont-Ferrand	758	366	5 536	2 413	38 186	18 771	12.32	3.10	177.0	82.3	614	526	551	447
Colmar	502	269	1 968	964	11 509	5 510	4.07	1.03	58.5	27.2	203	174	182	148
Creil	408	261	1 738	931	8 825	5 308	4.07	1.03	58.5	27.2	203	174	182	148
Dunkerque	12 860	11 950	5 388	3 695	19 248	12 393	62.65	47.63	138.8	64.6	16 834	15 119	16 791	15 085
Grenoble	2 482	1 460	10 197	5 148	45 464	23 293	20.73	5.22	297.7	138.5	1 033	885	927	752
La-Rochelle	264	149	2 664	1 309	13 907	8 099	5.11	1.29	73.4	34.1	255	218	229	185
Le-Havre	46 061	30 324	22 169	11 605	32 608	16 440	14.58	4.81	181.5	84.4	1 937	1 394	1 864	1 296
Lens-Bethune	20 629	12 457	26 947	18 855	60 344	37 663	28.78	7.24	413.4	192.3	1 435	1 229	1 287	1 045
Lille	5 283	3 034	16 096	8 654	77 766	44 568	50.53	12.05	684.3	318.4	2 408	2 081	2 152	1 730
Lyon	16 289	12 985	32 479	14 965	179 652	78 735	70.00	21.41	912.6	424.6	5 228	4 379	4 906	3 952
Marseille	4 766	2 188	31 912	13 002	204 050	79 015	62.13	15.64	892.4	415.2	3 098	2 654	2 779	2 255
Montbeliard	826	562	2 707	1 226	17 210	8 684	5.88	1.48	84.4	39.3	293	251	263	213
Montpellier	601	276	5 976	2 517	39 058	18 767	13.01	3.27	186.9	86.9	649	556	582	472
Mulhouse	1 478	824	5 504	2 715	31 885	15 269	11.28	2.84	162.0	75.4	562	482	504	409
Nancy	2 087	1 193	6 990	3 687	36 815	24 142	48.78	32.25	232.8	108.3	3 948	3 565	3 865	3 473
Nantes	1 434	769	11 131	4 805	69 794	34 216	25.59	6.67	362.1	168.5	1 380	1 176	1 250	1 013
Nice	1 031	383	12 500	5 200	82 073	32 436	26.36	6.63	378.6	176.2	1 314	1 126	1 179	957
Paris-(urban-a	38 823	12 731	108 699	56 115	505 740	233 192	449.00	112.74	6 433.5	2 993.2	23 913	21 349	21 063	16 286
Reims	1 267	826	6 896	3 628	33 244	17 101	10.29	2.59	147.8	68.8	513	440	460	373
Rennes	719	385	5 777	2 622	34 869	18 387	12.49	3.14	179.4	83.5	623	533	558	453
Rouen	9 612	8 624	15 311	10 796	47 546	23 529	19.07	4.87	272.0	126.6	986	842	889	721
Saint-Etienne	1 282	570	6 657	2 937	38 455	18 437	15.53	3.91	223.0	103.8	774	663	694	564
Strasbourg	7 004	5 760	10 643	5 801	55 322	26 197	27.92	11.88	282.4	131.4	3 655	2 993	3 558	2 841
Toulon	865	320	9 576	3 718	60 430	25 161	22.92	5.77	329.3	153.2	1 143	979	1 025	832
Toulouse	2 181	1 311	23 245	13 892	108 452	52 902	34.02	8.70	485.4	225.8	1 760	1 504	1 586	1 286
Tours	987	472	7 387	3 649	40 177	21 231	14.23	3.58	204.4	95.1	710	608	637	517
Valenciennes	1 671	882	5 673	3 049	33 618	21 719	16.81	4.23	241.4	112.3	838	718	752	610
Athinai	29 619	46 561	72 714	71 384	217 927	82 323	158.27	39.48	2 159.3	1 133.2	10 123	12 355	8 877	10 277
Thessaloniki	8 344	12 498	17 758	17 127	47 812	17 837	38.10	9.25	526.3	276.2	2 413	2 987	2 108	2 480
Dublin	17 038	6 730	15 103	9 293	68 171	38 440	23.77	5.35	446.0	124.6	5 790	5 605	5 608	5 262
Bari	589	306	5 563	2 497	47 554	27 329	7.55	1.36	221.4	88.6	991	961	934	894
Bologna	501	299	9 509	4 764	62 170	42 731	8.99	1.42	262.3	105.0	1 544	3 440	776	561
Catania	471	241	6 073	2 888	34 624	18 235	7.13	1.14	214.1	85.7	529	504	475	437
Firenze	798	436	6 823	3 168	45 144	25 547	8.69	1.39	261.0	104.4	645	615	580	533
Genova	11 816	7 344	25 965	14 787	114 341	75 045	16.45	4.39	438.3	175.4	3 230	3 041	3 102	2 905
Livorno	1 030	763	4 839	3 350	28 941	20 052	3.62	0.58	108.6	43.5	269	256	241	222
Messina	353	176	6 344	2 703	27 401	15 460	5.88	0.94	176.8	70.7	437	416	393	361
Milano+	3 220	1 786	23 967	12 307	157 808	83 683	44.04	14.70	948.0	379.3	17 796	50 922	5 455	2 373
Modena	463	318	4 317	2 567	30 605	22 378	3.80	0.61	114.3	45.7	283	269	254	233
Napoli	7 615	4 587	20 804	10 697	130 759	68 867	44.15	27.99	684.2	273.8	7 800	7 795	7 592	7 567
Palermo	896	453	13 188	5 920	82 462	44 562	15.05	2.41	452.3	181.0	1 118	1 065	1 004	924
Piacenza	5 046	2 973	7 163	4 215	20 417	16 567	2.52	0.66	66.3	26.5	961	947	944	930
Ravenna	466	304	4 018	2 400	26 476	19 104	2.92	0.47	87.9	35.2	217	207	195	179
Reggio-nell-em	346	221	3 239	1 897	18 706	13 702	2.84	0.45	85.3	34.1	211	201	189	174
Roma	6 866	3 734	45 869	22 795	317 786	157 931	58.23	9.38	1 747.4	699.2	4 835	4 566	4 389	4 020
Sassari	316	179	2 059	1 157	12 437	7 863	2.53	0.40	75.9	30.4	188	179	169	155
Siracusa	859	593	3 548	2 331	16 182	9 521	2.72	0.44	81.8	32.7	202	193	182	167
Terni	115	52	3 878	2 410	29 875	24 501	2.32	0.37	69.6	27.9	172	164	155	142
Torino	1 985	1 234	20 264	10 586	115 691	68 998	29.67	13.48	624.1	249.7	2 973	2 933	2 811	2 738
Trento	336	195	2 791	1 559	14 619	11 716	2.18	0.35	65.6	26.2	162	154	146	134
Venezia	1 161	632	7 720	4 491	37 151	22 034	6.76	1.15	200.3	80.1	1 074	979	1 017	917
Verona	524	299	6 469	3 431	37 323	27 726	5.46	0.87	163.9	65.6	405	386	364	335
Luxembourg	1 643	1 402	2 939	1 670	12 194	7 510	2.63	0.62	39.1	17.9	200	153	177	129
Amsterdam	2 572	2 146	18 873	10 016	67 495	30 925	11.91	17.30	467.2	221.8	2 098	2 016	2 579	2 040

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Apeldoorn	149	20	3 515	1 549	12 859	6 160	1.62	2.35	63.5	30.2	285	274	351	277
Dordrecht	483	378	7 394	5 178	16 052	8 038	2.31	3.36	90.6	43.0	407	391	500	396
Eindhoven	2 354	1 609	23 970	10 845	26 539	13 751	4.47	6.20	167.4	79.5	752	722	924	731
Haarlem	206	48	2 287	1 534	10 392	5 762	2.31	3.35	90.6	43.0	407	391	500	395
Heerlen	387	103	3 522	1 959	16 940	9 301	2.93	4.25	114.8	54.5	516	495	634	501
Kerkrade														
Nijmegen	266	130	4 029	2 697	10 486	5 403	1.59	2.32	62.5	29.7	281	270	345	273
Rotterdam	11 756	14 848	32 563	24 229	72 419	37 249	12.50	18.16	490.5	232.8	2 203	2 116	2 707	2 142
Vlaardingen														
s-Gravenhage	538	65	7 844	4 481	35 238	16 773	9.24	10.92	294.9	140.0	1 324	1 272	1 628	1 288
Utrecht	577	131	15 158	7 351	41 455	19 858	6.01	8.59	231.9	110.1	1 042	1 001	1 280	1 013
Zaanstad	228	60	1 490	1 196	6 461	3 870	1.59	2.32	62.6	29.7	281	270	345	273
Lisbao	19 679	12 152	20 940	10 569	132 963	68 558	174.32	27.43	1 617.2	568.8	4 453	5 326	3 588	4 029
Porto	12 811	6 607	14 350	7 016	94 730	50 536	120.51	16.32	1 145.6	402.9	2 952	3 512	2 344	2 601
Setubal	331	177	748	391	5 032	3 493	10.57	1.38	101.1	35.6	204	258	149	177
Goteborg	2 663	1 989	14 009	8 496	42 813	20 425	13.99	3.99	505.2	319.7	2 500	2 208	2 461	2 154
Jonkoping	482	382	3 616	2 083	12 137	6 487	3.44	0.86	130.5	82.6	248	226	236	208
Karlstad	613	509	2 285	1 564	6 499	3 553	1.59	0.40	60.4	38.2	115	105	109	96
Linkoping	618	498	4 403	2 822	12 815	6 713	3.91	0.98	148.3	93.8	282	257	268	237
Lund	387	296	2 100	1 304	6 377	3 106	1.93	0.49	73.5	46.5	140	127	133	117
Norrkoping	536	417	3 630	2 209	12 040	6 181	3.69	0.93	140.1	88.6	271	247	259	228
Orebro	471	370	3 557	2 094	12 828	6 714	3.55	0.89	134.8	85.3	256	234	244	215
Stockholm	3 200	2 270	23 118	14 056	77 456	36 778	26.45	6.75	1 000.2	632.9	1 951	1 791	1 861	1 653
Uppsala	1 111	1 016	6 912	4 550	17 374	9 339	5.49	1.48	205.9	130.3	427	399	408	371
Belfast	8 658	3 719	10 884	5 583	44 093	15 683	7.75	1.63	209.2	90.4	858	615	787	521
Bristol	3 067	1 783	6 373	3 137	24 696	7 867	9.46	1.82	281.2	121.4	677	556	579	429
Cardiff	5 098	4 029	9 901	7 670	14 879	5 368	13.26	8.10	211.3	91.3	1 091	989	1 014	886
Coventry	2 506	1 557	2 859	1 923	9 181	3 147	7.17	1.38	213.1	92.0	516	425	442	328
Doncaster	42 526	12 389	19 986	8 692	17 445	6 218	8.16	1.81	206.0	89.0	878	625	809	531
Edinburgh	5 352	3 157	10 849	6 313	39 385	12 112	10.51	2.02	312.4	134.9	752	618	644	477
Glasgow	6 620	3 532	18 427	9 058	75 147	22 368	23.10	10.22	478.9	206.8	5 123	5 031	4 951	4 763
Greater-Manche	56 022	32 533	43 117	29 948	101 900	35 649	62.52	11.24	1 633.6	705.5	4 299	3 487	3 714	2 663
Kingston-u-Hull	6 452	4 500	8 794	5 686	24 218	7 768	6.45	1.29	189.6	81.9	488	404	422	318
Leicester	5 235	3 004	7 073	3 697	25 660	8 124	6.98	1.35	206.6	89.2	534	429	462	336
Liverpool	32 947	23 018	26 669	20 613	56 356	19 985	37.63	10.09	992.7	428.7	4 331	3 695	3 962	3 218
London	163 139	68 795	169 096	90 755	492 958	162 257	306.80	83.80	7 444.4	3 214.9	23 138	17 777	20 530	14 161
Nottingham	2 924	1 654	5 146	2 566	22 626	7 031	6.69	1.29	198.9	85.9	479	394	410	304
Plymouth	3 423	2 198	10 284	6 146	35 064	11 509	6.06	1.16	180.2	77.8	434	356	371	275
Sheffield/Roth	5 441	3 050	11 588	5 731	44 001	13 908	40.73	24.40	553.8	239.2	2 865	2 616	2 657	2 304
Southampton/e	2 450	1 547	4 508	2 433	15 941	4 825	9.72	5.06	149.1	64.4	2 481	2 201	2 401	2 103
Stevenage	1 220	648	1 597	836	5 521	1 749	1.77	0.34	52.7	22.7	127	104	108	80
Stoke on Trent	7 568	3 062	9 166	4 268	35 773	11 134	16.29	2.99	265.8	114.8	906	723	795	524
Sunderland	4 135	2 523	3 954	2 915	11 390	3 922	13.33	1.67	209.3	90.4	622	506	531	334
Teesside	18 675	13 277	18 894	17 562	26 120	11 650	41.42	30.31	268.7	116.0	8 394	8 364	8 262	8 072
Tyneside	14 930	7 737	11 743	8 207	29 846	10 338	19.06	3.80	546.7	236.1	1 527	1 205	1 339	958
West-Midlands	22 569	12 191	22 288	14 327	63 316	21 819	55.63	10.06	1 465.1	632.7	3 926	3 166	3 403	2 432
West-Yorkshire	48 503	24 606	35 098	21 976	89 891	30 338	36.64	7.15	1 073.0	463.4	2 754	2 220	2 383	1 735